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Sustainable soil use and management: An interdisciplinary and systematic approach

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HIGHLIGHTS

- Soil degradation impedes achieving the United Nations' Sustainable Development Goals.
- Soil plays a fundamental role for biodiversity conservation.
- Soil researchers ought to prioritize the multifunctional value of soil health.
- A framework for interdisciplinary research in soil sustainability is presented.
- Information management and knowledge sharing may drive sustainable behavior change.

GRAPHICAL ABSTRACT

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ABSTRACT

Soil is a key component of Earth's critical zone. It provides essential services for agricultural production, plant growth, animal habitation, biodiversity, carbon sequestration and environmental quality, which are crucial for achieving the United Nations' Sustainable Development Goals (SDGs). However, soil degradation has occurred in many places throughout the world due to factors such as soil pollution, erosion, salinization, and acidification. In order to achieve the SDGs by the target date of 2030, soils may need to be used and managed in a manner that is more sustainable than is currently practiced. Here we show that research in the field of sustainable soil use and management should prioritize the multifunctional value of soil health and address interdisciplinary linkages with major issues such as biodiversity and climate change. As soil is the largest terrestrial carbon pool, as well as a significant contributor of greenhouse gases, much progress can be made toward curtailing the climate crisis by sustainable soil management practices. One identified option is to increase soil organic carbon levels, especially with recalcitrant forms of carbon (e.g., biochar application). In general, soil health is primarily determined by the actions of the farming community. Therefore, information management and knowledge sharing are necessary to improve the sustainable behavior of practitioners and end-users. Scientists and policy makers are important actors in this social learning process, not only to disseminate evidence-based scientific knowledge, but also in generating new knowledge in close collaboration with farmers. While governmental funding for soil data collection has been generally decreasing, newly available 5G telecommunications, big data and machine learning based data collection and analytical tools are maturing. Interdisciplinary studies that incorporate such advances may

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lead to the formation of innovative sustainable soil use and management strategies that are aimed toward optimizing soil health and achieving the SDGs.

Contents

1. Introduction

Soil, commonly viewed as a non-renewable resource due to the extremely slow pace of its regeneration, is under serious threat from modern society (Amundson et al., 2015). Soil degradation occurs due to factors such as water erosion, wind erosion, salinization, and deforestation (Carlson et al., 2012; Celentano et al., 2017; Rojas et al., 2016). Activities that introduce polluting substances, such as heavy metals, pesticides, polycyclic aromatic hydrocarbons (PAHs), are further causing wide-spread soil degradation. Globally, it is estimated that ~24 billion metric tons of soil are lost through factors such as erosion each year (UNCCD, 2017) and that ~30% of the world's soils are now in a degraded state (FAO, 2011). In China, ~19% of agricultural soil and ~ 16% of all soils exceed national soil quality standards (MEP, 2014). Soil degradation threatens the realization of the United Nations Sustainable Development Goals (SDGs) (Bouma, 2019). To help address soil degradation, the United Nations Food and Agriculture Organization declared 2015–2024 as the International Decade of Soils, aiming to raise public awareness of soil protection. Since then, there has been a burgeoning trend of scientific literature and public debate on soil.

Soil is primarily viewed as a critical component of agricultural production in traditional wisdom. In more recent years, the scientific community has increasingly recognized that soil is also an essential component for environmental protection (Obrist et al., 2017), climate change mitigation (Le Quere et al., 2018), ecosystem services (Bahram et al., 2018), as well as land use and planning (Gossner et al., 2016). There is also a growing recognition that soil health relates not only to the classical biogeophysical processes that are traditionally studied by soil scientists, but also information management, knowledge sharing, and human behavior (Bampa et al., 2019; Bouma et al., 2019). Interdisciplinary studies (see Section 2.3) are required to understand better the coupling of complex human-nature systems linked to soil management (Bouma and Montanarella, 2016). However, current knowledge on soil processes is scattered across various disciplines, lacking comprehensive views on the sustainable management of soil resources (Vogel et al., 2018).

In 2015, the United Nations General Assembly established 17 goals to be achieved by 2030, which are named the Sustainable Development Goals (SDGs). These include, among others, no poverty, zero hunger, good health and wellbeing, clean water and sanitation and climate action (UN, 2015). The SDGs have become a central theme of global development and international collaboration. Considerable progress has been made in recent years toward reaching the SDGs. For example, the proportion of the global population with access to safe drinking water and the percentage of children receiving vaccinations have both risen considerably. However, many challenges still exist, such as: 821 million people remain undernourished, representing a 5% increase between 2015 and 2017; investment in agriculture from governmental sources and foreign aid has dropped; and, atmospheric concentrations of CO_2 and other greenhouse gases (GHGs) continue to rise (UN, 2019), exacerbating the current climate crisis. Governments from local to national levels need to develop integrated programs addressing these sustainability challenges (Bryan et al., 2018).

In the ongoing actions toward reaching the United Nations SDGs, the soil science community has somewhat underplayed the potential role it could play, partly due to the scattered nature of soil knowledge mentioned above. If researchers from wider disciplines were to collaborate more with soil scientists, it may help progress approaches to achieving the SDGs in a manner more effective than acting alone. Therefore, the profile of the soil science discipline may need to be raised, especially the interdisciplinary components that support food security, climate change mitigation, biodiversity, and public health, in order to better design comprehensive strategies toward realizing the SDGs.

In the present paper, we do not reiterate the importance of the interaction between soil science and agronomy covering crop productivity, which has been discussed in other existing publications (Sanchez, 2002; Tisdale et al., 1985). Instead, we focus on the interdisciplinary nature of soil and sustainable soil use and management and linkages with soil science with social science, climate science, ecological science, and environmental science.

2. The interdisciplinary nature of sustainable soil use and management

2.1. Sustainable development goals (SDGs)

Soil plays a pivotal role in the United Nations SDGs, most notably SDGs 2, 3, 6, 12, 13, and 15 (Bouma and Montanarella, 2016; Keesstra et al., 2016). Most people in poverty live in rural areas where crop production is a vital source of income. In these areas, soil health is a decisive factor for productivity and income levels. Among other roles, soil provides the basis for food production and ecosystem services (Bender et al., 2016; Oliver and Gregory, 2015). Moreover, as soil biodiversity is related to lower crop diseases and pests, the ecological services offered by healthy soil systems are important in reducing poverty and ending hunger. Soil also affects water quality, GHG emissions, and other important environmental considerations in regard to the SDGs (Bharati et al., 2002; Franzluebbers, 2005). An overview of the identified relationships between soil and the relevant SDGs are illustrated in Fig. 1.

It is imperative to disseminate soil science knowledge to policy makers and practitioners who design and implement SDG programs (see Section 3). Effective action needs to be taken by the soil science community to help develop suitable indicators that are not only scientifically sound, but also practical for small hold farmers and other stakeholders. Scientific research needs to be specifically directed toward realizing the SDGs, rather than to just understand soil science. The influence of human behavior must be factored into this complex human-nature system. It is also necessary to include the impacts of socio-economic activity on soil health when carrying out sustainability assessments, thus allowing more informed decision making (Vogel et al., 2018).

2.2. The soil health concept

Soils have a wide range of physical, chemical, and biological properties that are attributable to the parent material (e.g., geologic origin and depositional processes), environmental factors (e.g., climate conditions, topography) as well as anthropogenic influences (e.g. farming practice, surface disturbance, pollutant emissions). Because soil plays such a critical role in multiple natural and anthropogenic systems, such soil properties will affect ecosystem services, environmental quality, agricultural sustainability, climate change, and human health. This multi-functional aspect makes traditional soil quality evaluation systems, which have tended to focus on soil fertility and agricultural production (Doran and Parkin, 1994), no longer fully appropriate. Most recently, the "soil health" concept has been the subject of increasing research attention (see Fig. 2). This holistic approach accounts for non-linear mechanistic relationships between various physical, chemical, and biological properties. Moreover, the soil health holistic concept is advantageous over traditional soil quality assessments because it considers ecosystem services as well as agricultural production, i.e., both nature and human driven objectives (Kibblewhite et al., 2008).

Doran and Zeiss (2000) defined soil health as "the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" Their definition has been well received by the scientific community, as evidenced by the article being cited ~1500 times according to Google Scholar. The authors argued that soil health is a holistic concept which portrays soil as a living system (i.e., the capacity of soil to function as a living system), while soil quality describes a soil's capacity for a specific use (i.e., fitness for different uses). The outcomes of soil use and management decisions are reflected in soil health (Doran and Safley, 1997).

Assessing soil health involves the selection of indicators, quantification or qualitative scoring, and providing a final index with appropriate weighting and integration (Rinot et al., 2019). Biophysical indicators are particularly relevant for assessing soil health. This is because healthy soil is manifested through a variety of soil functions that are reliant upon biological processes, e.g. carbon transformation, nutrient cycling, maintaining soil structure, and regulating pests and disease (Kibblewhite et al., 2008). Scientists have explored the use of soil micro-organisms (Nielsen et al., 2002; Van Bruggen and Semenov, 2000), enzyme activities (Ananbeh et al., 2019; Janvier et al., 2007), earthworms and nematodes (Neher, 2001), as well as other biological indicators to assess soil health. Similarly, soil structure, compaction and moisture retention have been used as physical indicators of soil health.

Fig. 1. The relevance of soil to the United Nations' Sustainable Development Goals (SDGs).

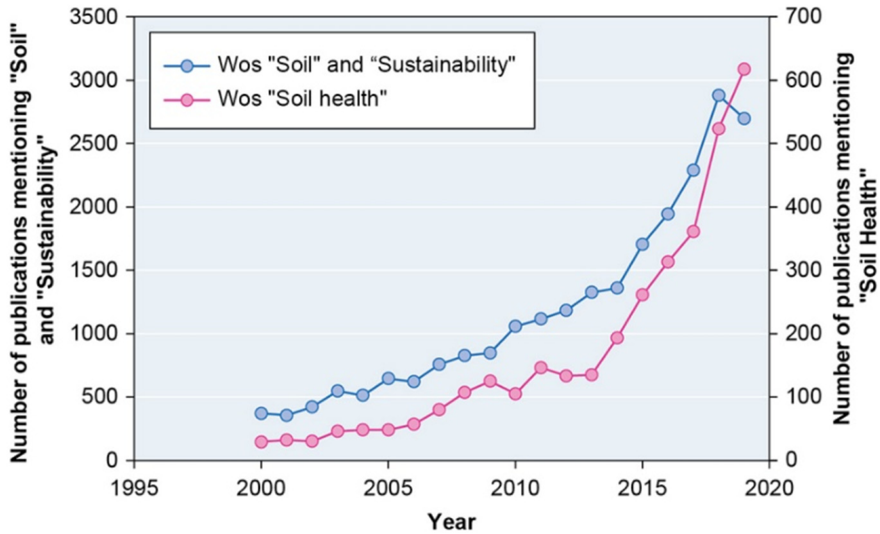

Fig. 2. Number of research articles listed in the Web of Science database (www.webofknowledge.com) when soil AND sustainability and "soil health" were searched as topics (searched on 3rd March 2020).

2.3. Interdisciplinary research

The sustainability of soil systems is affected by their bio-physico-chemical properties, and the soil use and management decisions made by farmers (Doran and Zeiss, 2000). These two aspects can be broadly categorized into natural and anthropogenic processes. Complex dynamics are involved in the coupled human-nature systems, rendering many challenges for the study of soil systems from any single disciplinary lens. We must develop an interdisciplinary approach to address these challenges (Totsche et al., 2010). It should be noted that interdisciplinary approaches differ from multidisciplinary approaches, in that they integrate insights on a common problem (e.g. climate change) from different disciplines (e.g. soil science and climate science) to construct a comprehensive understanding of the issue. In comparison, multidisciplinary approaches involve gaining separate insights on a common problem from the perspectives of different disciplines (Repko and Szostak, 2020).

As many of the problems surrounding soil sustainability are complex and broad, they cannot be sufficiently addressed by one single discipline, thus interdisciplinary studies are needed (Klein and Newell, 1997). Based on a published framework that interconnected disciplinary lines for another topic (Hammond and Dubé, 2012), here we propose a general framework for developing an interdisciplinary perspective on sustainable soil use and management (Fig. 3). We propose that five broad issues have a root in soil science and are linked to at least one other discipline. The issues themselves are also interconnected. Take management and behavior as an example, which is directly linked to soil science and social science. At the same time, soil fertility and soil pollution are also involved, which are directly linked to agronomy and environmental science, respectively. Another example is soil carbon (or soil organic matter) which is directly linked to both soil science and climate science while also affecting soil biodiversity linked to ecology, and soil fertility linked to agronomy. In a sense, the network shown on Fig. 3 forms a complex six-disciplinary system, which can be used for studying soil sustainability.

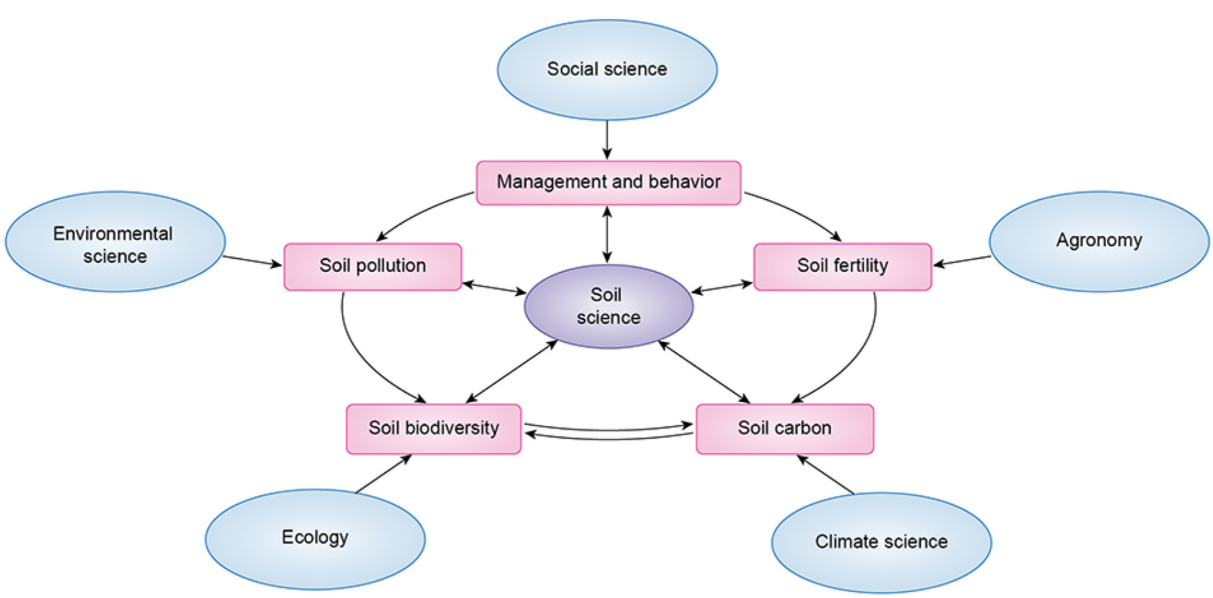

Fig. 3. A framework for interdisciplinary research in soil sustainability linking soil science with social science, environmental science, ecology, climate science, and agronomy.

3. Soil and social science

3.1. Knowledge transfer

A myriad of scientific knowledge exists regarding best practice for soil management. However, there has been a general lack of adoption by farmers (Bouma, 2019). This can be attributed to obstacles that hinder the distribution of relevant scientific information. Scientific evidence from in-depth studies is often scattered within various disciplines that use technical jargon that is little understood by the social scientists or journalists who are engaged in information transmittal and knowledge sharing. Modern electronic information sharing techniques, including social media tools (e.g., Twitter and Facebook), make mass information distribution easier (Mills et al., 2019), but they can also make it difficult for lay people to distinguish between evidence-based reliable information and inaccurate or even misleading information. A parallel example occurred during the novel coronavirus disease (COVID-19) outbreak, during which large amounts of misinformation were transmitted across social media. Scientists felt the need to publish a joint statement to denounce such rumors (Calisher et al., 2020).

Information management and knowledge sharing may help to fill the gap between knowledge generation and its useful application. This is particularly important for the application of soil science. A variety of soil information management and knowledge sharing mechanisms exist, including training workshops (online or offline), websites, social media, advisory services. In Australia, the New South Wales local government uses webinars to disseminate soil science information to a geographically disperse community of practice (CoP) (Jenkins et al., 2019). Grain advisors, however, were reported to be guiding farmers to historically established “rules of thumb” for calculating nitrogen fertilizer needs, rather than the latest evidence-based science on soil water and nitrogen management (Schwenke et al., 2019). Another Australian local government decided to share soil information and knowledge using a website coupled with training workshops. The type of information shared may include soil properties and landscape characteristics obtained from field assessment studies. Such initiatives show that centralized knowledge sharing can bring significant tangible benefits (Imhof et al., 2019). However, a 10-year follow-up survey showed that while training workshops could be effective in the short term, behavioral change was not sustained in the long term. It was suggested that continuing professional development to upskill farm advisors and the CoP may render a more persistent uptake of knowledge at the farm level (Andersson and Orgill, 2019).

In Europe, both private and public sector advisors, operating on national, provincial or local levels offer science communication to farmers (Ingram and Mills, 2019). In Switzerland, sustainable soil management knowledge was successfully shared among farmers via social learning in a video format (Fry and Thieme, 2019). A study in the English East Midlands suggested that soil advisors ought to incorporate hands-on practical knowledge (Stoate et al., 2019). This concurs with another study in Australia, which showed that establishing a network of senior ex-governmental soil scientists and farmers enabled effective soil knowledge transfer (Packer et al., 2019).

As precision agriculture incentivizes the use of sensing technologies to collect soil data, it becomes increasingly important to form public-private partnerships to collect, store, and use the huge amounts of geographically referenced soil data generated (Robinson et al., 2019). The emerging fifth generation of wireless technology for digital cellular networks (5G), big data, and machine learning offer data collection and analysis techniques that may enable a new generation of soil information sharing tools. Within the 5G system, an internet of things (IoT) can be established with low latency, enabling real time soil measurement and response. For instance, unmanned aerial vehicle (UAV) based remote sensing can be coupled with soil amendment delivery in precision agricultural practice (Kota and Giambene, 2019; Morais et al., 2019). Big data applications with machine learning also provide predictive power, facilitating smart farming to save energy, water, and cost, while increasing crop yields (Wolfert et al., 2017).

3.2. Farmer behavior

The sustainability of soil use and management is ultimately reliant on the real-world behavior by practitioners, most particularly farmers. Therefore, there is a growing interest to integrate social components and farmer behavior with the ecological component of soil management (Amin et al., 2019). In modern society, with the fast-growing use of various types of information technology, farmer behavior can be influenced by different network-based approaches. For instance, a study in Europe found that farmers formed a learning network by sharing information and soil knowledge on the microblogging and social networking service, Twitter. This platform has a limited length for each message (280 characters for non-Asian languages), making it easy for time-constrained farmers to follow (Mills et al., 2019). In the US, an integrated network-based approach enabled a quarter of respondents to adopt cover crops for weed control, and respondents also increased their follow-up usage from information shared on Twitter (22%), YouTube (23%), and web sites (21%) (Wick et al., 2019).

Farmer behavior and farming practice is also directly affected by professional advisors. In Australia, farmers apply the recommendations of professional crop advisors to select suitable fertilizer dosages. However, attitudes concerning financial risk, soil heterogeneity, and local climate conditions can affect their perception and adoption of such advice (Schwenke et al., 2019). In Europe, a knowledge gap regarding sustainable soil management was identified as a major issue among both farmers and soil advisors. As the current trend of privatization and decentralization of advisory services continues, there is an increasing need to educate those who provide advisory services, thus enabling effective empowerment of farmers (Ingram and Mills, 2019). Governments ought also to provide workshops that encourage farmers to adopt greater soil testing, so that they can then make informed soil management decisions (Lobry de Bruyn, 2019).

Lack of education and awareness creates an obstacle for sustainable soil use and management, especially in developing countries. For example, it was found that farmer perception strongly correlates to adoption rates for conservation agriculture ($r = 0.81$; $p < 0.05$) (Mugandani and Mafongoya, 2019). It has been reported that concerns over soil type, weed control, and weather conditions were the main inhibiting factors when English farmers consider reduced tillage practice. The authors suggested that enhanced adoption of sustainable soil management practice will require improved communication between the soil research community and farmers (Alskaf et al., 2020).

3.3. Stakeholders

The creation, dissemination and usage of soil sustainability knowledge involves a wide range of stakeholders, such as scientists, farmers, land managers, advisory services, commercial product suppliers, regulators, funding agencies, educators, students, as well as the general public (Knox et al., 2019; Tulau et al., 2019). Different stakeholders will have different concerns. Farmers and crop advisors are primarily concerned about local soil knowledge, while regulators and scientists are more concerned about policy, scientific solutions and the wider environment (Bampa et al., 2019). There is also a dynamic interaction and potential gap between awareness and perception, i.e., what can be done and what is worth doing (Krzywoszynska, 2019). Based on an analysis in England, Krzywoszynska (2019) argued that interactions between soil researchers and end users are multifaceted and that these actors must work together on both knowledge generation and knowledge sharing to enhance sustainable behavior.

Scientists and governments are pivotal stakeholders in promoting sustainable soil use and management practices. Their action can enhance the robustness of scientific knowledge creation and broaden its applicability by incorporating evidence into policy instruments. In Scotland, soil risk maps are created by scientists, policy makers and industrial representatives working in close collaboration (Baggaley et al., 2020). Similarly, in Australia, soil constraints maps have been produced for site-specific management (van Gool, 2016). Such tools can help mitigate constraints to achieving climate-driven genetic yield potential of agricultural crops. Models that incorporate learnings from stakeholder engagement can also render strong predictive power (Inam et al., 2017). Traditionally, the main channel of soil knowledge generation has been government funded. However, there has been a general decreasing trend in the provision of government funds for soil data collection in many developed countries, while privately funded collection of soil information has increased dramatically (Robinson et al., 2019). Under this situation, it is even more important to bring in additional stakeholders to create and share soil knowledge. The Soil Knowledge Network (SKN) in Australia demonstrated that ex-governmental soil scientists can exert long-lasting positive impacts by coaching new generations of early career soil scientists (McInnes-Clarke et al., 2019).

4. Soil and climate science

4.1. Soil organic carbon

Soil organic carbon (SOC) has been recognized as a critical indicator of soil health, because it reflects the level of soil functionality associated with soil structure, hydraulic properties, and microbial activity, thereby integrating physical, chemical and biological health of soil (Vogel et al., 2018). Recently, increasing attention has been placed on SOC beyond the traditional sphere of soil science. This is because it is a key component of Earth's carbon cycle, thus having huge implications for the current climate crisis (Kell, 2012) and SDG13: Climate action. Soil is the largest terrestrial carbon pool, holding an estimated 1500–2400 GtC and permafrost (i.e. frozen soil) storing 1700 GtC (Le Quere et al., 2018). A global initiative known as '4 per 1000', which aims to increase soil organic carbon by 0.4% per year, would result in an additional carbon storage of 1.2 GtC per year if successful (Paustian et al., 2016; Rumpel et al., 2018). In Australia, surface soils provide a significant reservoir of carbon, holding ~19 billion metric tons. However, most of these soils (~75%) contain <1% SOC, suggesting huge additional capacity for carbon sequestration. An annual 0.8% increase in carbon storage across all Australian surface soils would fully offset the nation's GHG emissions (Baldock et al., 2010)

Soil properties and vegetation are affected by the climatic condition (Bond-Lamberty et al., 2018). For example, global warming may accelerate soil erosion due to its impact on microorganisms and plant and animal species (Garcia-Pichel et al., 2013). Moreover, different soil types and land use systems are unevenly sensitive to temperature changes. Soil carbon that is normally recalcitrant in semi-arid regions is vulnerable to rising temperature (Maia et al., 2019). Therefore, soil management practice in these areas may have a tremendous effect on carbon cycling.

Organic fertilizer applications can improve soil functionality and significantly increase SOC levels. Thus, applying organic amendments, including biosolids and composts, to agricultural land can increase carbon storage and contribute significantly to offsetting GHG emissions. Studies have shown that manure can potentially increase crop yields and soil organic contents in comparison with mineral fertilizers (Jing et al., 2019). A 37-year field study showed that organic fertilization increased soil carbon input by 25% to 80%, although levels of carbon retention ranged from only 1.6% for green manure to 13.7% for fresh cattle manure (Maltas et al., 2018). Similarly, Bolan et al. (2013) demonstrated that biosolid applications likely result in higher levels of carbon sequestration compared to other management strategies including fertilizer application and conservation tillage. This was attributed to an increased microbial biomass, and Fe and Al oxide-induced immobilization of carbon (Bolan et al., 2013). In comparison with open-air systems, the use of organic fertilizers for indoor greenhouse soils may have a greater positive influence on soil functionality due to its effect on porosity and pore connectivity (Xu et al., 2019). It should be noted that organic fertilizers may not increase crops yields to the levels achievable with inorganic fertilizers. This issue can be overcome by supplementing organic fertilizers with inorganic ones (Maltas et al., 2018).

A variety of conservation farming practices can increase SOC levels, while also increasing crop productivity and decreasing water demand (Kumar et al., 2019; Mehra et al., 2018). Crop residue return to surface soils can have a positive effect on soil carbon sequestration (Chowdhury et al., 2015; Li et al., 2019b). For example, chopping and returning wheat straw and corn stover can increase SOC levels by 14.5% in a double-cropping system (Zhao et al., 2019). Reduced tillage and non-tillage practices can also increase soil SOC levels (Chatskikh et al., 2008; Lafond et al., 2011). For example, a 22-year study showed that with no tillage, mulch treatment had a significantly positive effect on carbon retention (Kahlon et al., 2013). Integrated methods have the potential to achieve even more significant increases in SOC levels. For example, SOC data collected over 35 years in a semi-arid region of China showed that carbon levels were enhanced (by 453% to 757%) using a combination of best practice cultivation, mulching, and planting methods (Guoju et al., 2020). Different land uses also affect SOC, not only in terms of concentration, but also the fractions of SOC that are vulnerable to mineralization (Ramesh et al., 2019). For example, labile and humified SOC fractions have been reported to be more prone to mineralization in arable lands than in grasslands (Ukalska-Jaruga et al., 2019).

Accurate quantification of SOC remains a challenge because of high spatial heterogeneity in soils. For instance, features such as hedgerows and fences can influence SOC due to their impact on soil moisture and bulk density (Ford et al., 2019). Soil compaction by agricultural machinery reduces macropores and creates water ponding (Mossadeghi-Björklund et al., 2019), which can affect SOC. There are also discrepancies between SOC estimates using regional versus local parameters, particularly for in woodland soils containing large amounts of decaying organic matter (e.g., Histosols) and low-input high-diversity ecosystems (Ottoy et al., 2019).

4.2. Biochar as a mitigation

Biochar is a carbon rich product that is produced by the burning of biomass with a limited supply of oxygen (i.e., pyrolysis) (Lehmann and Joseph, 2009; Wang et al., 2020c). It typically possess a stable fixed carbon structure with high porosity, a high specific surface area and a high alkalinity. These characteristics enable biochar to enhance soil moisture content, sorb polluting substances and increase soil pH (Andrés et al., 2019). Moreover, biochar is considered carbon negative because the carbon within its structure, which is captured from the atmosphere during biomass formation, is more recalcitrant in the natural environment than carbon in biomass that has not been pyrolized. Because of its carbon negativity and beneficial properties for soil management, biochar has been proposed as a possible technology to help mitigate climate change (Woolf et al., 2010). Numerous studies have explored the usage of biochar in croplands (Laird et al., 2010b), while recent studies have also examined its application in other systems, such as alpine grassland (Rafiq et al., 2019).

At the current carbon price, applying biochar to soil is not commercially viable unless there is an additional benefit to farmers. Therefore, researchers have conducted extensive research on the benefits biochar for agricultural and environmental purposes. One of the most researched areas is the use of biochar to increase crop yields. A recent meta-analysis found that in comparison with inorganic fertilizer alone, biochar can increase crop yields by 11% to 19% (95% confidence intervals) (Ye et al., 2020). Biochar has also been put forward as a sustainable technique for remediating soils degraded by contaminants, especially heavy metals (Hou, 2020; O'Connor et al., 2018c; Song et al., 2019). The sustainability of biochar is increased if the biomass feedstock is a biological waste that would otherwise be burned or discarded at landfill, thus avoiding air pollution or the consumption of landfill space. However, while a myriad of studies have shown biochar applications have positive effects on soil, it should be noted that such effects may diminish after 3– 5 years (Dong et al., 2019). Biochar effectiveness and longevity may be enhanced by the invention of engineered biochars (O'Connor et al., 2018b).

4.3. Soil greenhouse gases

Soils act as significant sources of various greenhouse gases (GHGs), including CO_2, CH_4, and N_2O. Reducing the emission of such GHGs is one of the greatest challenges for sustainable farming (de Araújo Santos et al., 2019) and the achievement of SDG13: Climate action. Soil CO_2 emissions are affected by agricultural practice (e.g. tillage and fertilizer application), as well as the soil properties (e.g. soil texture). For sandy soils, greater macroporosity tends to be associated with higher CO_2 emissions, while microporosity is associated with lower emissions, which likely related to their respective tortuosity levels (Farhate et al., 2019; Tavares et al., 2015). The use of lime to treat low pH soils may also relate to CO_2 emissions. Therefore, sustainable management of low pH grasslands may involve the use of low liming dosage rates, which provide almost the same result as higher rates (Bolan et al., 2003; Kunhikrishnan et al., 2016; Lochon et al., 2019). A study in Denmark showed that reduced tillage practice can decrease net GHG emissions by 0.56 Mg CO_2-eq. ha^{-1} per year; moreover, the use of disc coulters that minimally disturb soil can reduce net GHG emissions by 1.84 Mg CO_2-eq. ha^{-1} per year (Chatskikh et al., 2008).

Atmospheric N_2O accounts for ~6% of radiative forcing caused by anthropogenic activity, which largely stems from soil systems (Davidson, 2009). Therefore, emission of N_2O from agricultural soil is particularly concerning. Davidson (2009) estimated that 2% of nitrogen in manures and 2.5% of nitrogen in fertilizers used by farmers over the period of 1860–2005 was converted to atmospheric N_2O. In China, emissions derived from synthetic nitrogen fertilizers account for ~7% of the nation's annual GHG budget. By implementing new technology and best management practices that minimize nitrogen use in soil management, it is feasible to reduce GHG emissions by 102–357 Tg CO_2-equivalent in China alone (Zhang et al., 2013). Soil amendment with more sustainable alternatives to synthetic nitrogen (e.g., biochar) may help reduce N_2O emissions from soil (Senbayram et al., 2019).

Methane emissions from soil represent another major factor for climate change. An early study found that the application of rice straw to paddy fields increased CH_4 emissions by a factor of 1.8 to 3.5 (Yagi and Minami, 1990). Recently, methane emissions from permafrost (permanently frozen soil) has drawn attention from the climate science community, owing to its critical role in carbon cycling (Schuur et al., 2015). As climate change occurs, rising temperature in the polar regions causes permafrost to thaw and microbial activity to increase (Hollesen et al., 2015). This leads to increased methane and CO_2 emissions from organic-rich Arctic soils (Schuur et al., 2013). As these gases are associated with increased global warming potential, their emission increases the levels of permafrost thaw, thus forming a positive feedback loop. It is imperative to understand these processes in a quantitative way. As the climate change crisis worsens, it may be necessary to take mitigating measures involving soil management in areas associated with high methane fluxes.

5. Soil biodiversity and ecology

5.1. Soil biodiversity

Sustainable soil management practice can improve or conserve soil biodiversity, which represent a significant proportion of Earth's total biodiversity (Bahram et al., 2018) and is pertinent to the achievement of the United Nations' SDGs (e.g., SDG15: Life on land). Among other factors, soil microbial communities are affected by the availability of nutrients corresponding to the type of soil management practice (Bolan et al., 1996; Lauber et al., 2009; Leff et al., 2015). For example, the use of soluble fertilizers (e.g., monocalcium phosphate), less soluble organic fertilizer (e.g., sugarcane filter cake) or nearly insoluble rock phosphate (Arruda et al., 2019) have different impacts on soil microbial communities. Soil management practices also affect soil hydraulics, which affects plant and microbial biodiversity and ecosystem resilience (Alley et al., 2002; Anderegg et al., 2018). A study in India reported that integrating crop residue return with green manure application and no-tillage in a rice-wheat double cropping system increased SOC levels by 13%, the microbial biomass by 38%, the basal soil respiration rate by 33%, and the microbial quotient by 30% (Saikia et al., 2020). Certain soil amendments are associated with increased soil biodiversity. For example, biochar amendment of a Mediterranean vineyard soil decreased the mineralization of both SOC and microbial biomass, while the functional microbial diversity and biodiversity of soil micro-arthropods were maintained (Andrés et al., 2019). Soil properties and biodiversity are also affected by plant root systems within the rhizosphere (Dey et al., 2012).

Larger species in soil are also an important aspect of soil biodiversity as well as being influential on soil properties (Bardgett and van der Putten, 2014; Wu et al., 2011). Earthworms (Oligochaeta) are a particularly important soil species due to their creation of soil macro-pores (>0.3 mm) and channels (burrows) that increase water and gas infiltration rates (Bartz et al., 2013; Bhadauria and Saxena, 2010). Thus earthworm activity can render soil environments that are more amenable to microbial activity and diversity (Eriksen-Hamel et al., 2009). Conservation tillage practices that involve crop residue return to surface soils can increase earthworm numbers by hundreds of thousands per hectare (Barthod et al., 2018; Giannitsopoulos et al., 2020)

5.2. Ecosystem services

Soils provide vital ecosystem services, rendering both economic and societal benefits (Adhikari and Hartemink, 2016; Dominati et al., 2010; Pavan and Ometto, 2018; Su et al., 2018). Monetary valuation methods have been put forward to account for the natural capital of this resource (Robinson et al., 2014). In this way, a national-scale study in the UK suggested that an additional £18 billion GBP of ecosystem services could be achieved under an optimal policy scenario. This value takes into account major ecosystem services, such as agricultural production, carbon sequestration, recreational usage, and wildlife diversity (Bateman et al., 2013). However, some scholars have argued that systematic monetarization is unnecessary. For example, Bayesian Belief Networks (BBNs) and Multi-Criteria Decision Analysis (MCDA) methods can provide decision makers with semi-quantitative information that takes into account the multifunctionality of soil ecosystem services (Baveye et al., 2016).

Living organisms in soil have a direct impact on agricultural productivity and ecosystem services. For instance, the microbial community is essential for the natural decontamination of polluted soils. Therefore, monitoring biological indicators is necessary for managing soil ecosystems effectively. Some of the most important soil biota indicators include microsymbionts, decomposers, elemental transformers, soil ecosystem engineers, soil-borne pests and diseases, and microregulators (Barrios, 2007). Soil invertebrates also play a significant role in soil ecosystem services (Lavelle et al., 2006).

In Europe, a large number of monitoring programs and field studies have been conducted since the 1990s, to gain data for optimizing ecosystem services (Pulleman et al., 2012). The data shows that spatial heterogeneity within soil systems translates into the uneven distribution of ecosystem services (Aitkenhead and Coull, 2019). Governments may intervene to restore or improve ecological services in limited soil systems. In China, for example, the government has made subsidies available to farmers to protect natural woodlands and convert steep agricultural cropland into other land uses, such as grassland or woodland (Liu et al., 2008). If farmland is degraded to an extent that it is abandoned, soil treatments may help bring about natural revegetation and the recovery of ecosystem services (Li et al., 2019a). For example, the recovery of severely degraded land can be facilitated by the use of soil amendments such as biochar (O'Connor et al., 2018c).

6. Soil and environmental science

6.1. Soil pollution

Contaminants are an issue for many agricultural sites (Bolan et al., 2014; Khan, 2016; O'Connor et al., 2019b; Wilcke, 2000), which hinders efforts toward the achievement of the United Nations' SDGs (e.g., SDG3: Good health and well-being). Soil contaminants include heavy metals, such as cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg) and zinc (Zn), and organic pollutants, such as pesticides and polycyclic aromatic hydrocarbons (PAHs). As an emerging contaminant, microplastics in the soil environment have also drawn attention in recent years (Bradney et al., 2019; Jia et al., 2020; O'Connor et al., 2020; Wang et al., 2020a). Assessment of their fate and transport is critical for understanding the environmental risk (Corradini et al., 2019; Wang et al., 2019a).

A global map of soil pollution is urgently needed to understand better the situation globally, but few countries are investing in national-scale investigations (Hou and Ok, 2019). Elevated levels of soil pollutants can result from a wide variety of anthropogenic activities, ranging from metal mining to fossil fuel burning (Zhang et al., 2020b). The spatial redistribution of these pollutants involves inter-phase transfer such as dissolution from soil to water, volatilization from soil to air, and deposition from air to soil (O'Connor et al., 2019a; Zhang et al., 2019). Anthropogenic soil pollution in under-developed regions where industrial activities are less intensive can also occur due to traffic and mining related emissions, etc. For instance, a recent study in a suburban area of Central Asia showed that Pb, Zn, and Cu can accumulate to high levels in soils because of road traffic up to 200 m away (Ma et al., 2019).

The remediation of contaminated soil is an important research field interlinking soil science and environmental science. Traditionally, remediation practitioners focused on either physical cleanup methods, such as soil excavation and disposal at landfill (Qi et al., 2020), or chemical treatment methods, such as in situ chemical oxidation (O'Connor et al., 2018a). In recent years, nature-based solutions, such as phytoremediation and green stabilization, have gained attention among the scientific research community (Wang et al., 2019b; Wang et al., 2020b; Zhang et al., 2020a). For example, microbial strains from unique natural environments are being harvested, cultured, and exploited to render economic and environmentally friendly solutions for soil decontamination (Atashgahi et al., 2018; Bunge et al., 2003).

6.2. Soil erosion

Soil erosion, a major land degradation process, is caused by the weathering effects of water and wind (Lal, 2003). For land covered by native vegetation, natural erosion rates will tend to balance with soil production rates. However, typical agricultural tillage practice can disrupt this balance, causing levels of soil erosion to be one to two orders of magnitude higher than that of soil formation (Montgomery, 2007b). Soil systems that experience net soil erosion can suffer the loss of fertile surface soils, removal of soil organic carbon, and reduced agricultural productivity, thus rendering a high environmental and economic cost globally (Montgomery, 2007a; Pimentel et al., 1995). Because heavy metals tend to bind strongly to eroded soil particles, the widespread distribution of soil pollutants is also often associated with soil erosion (Xiao et al., 2019).

Soil erosion not only causes damage to the land where it occurs, but also jeopardizes local aquatic systems due to excessive sediment loading (Boardman et al., 2019). Soil erosion models have been developed to predict impacts of water quality on a catchment-scale (Fu et al., 2019). It can also cause damage to nearby housing due to increased surface runoff and landslides. Because of such impacts, many governments are taking largescale mitigating action, such as revegetation with native species and woodland restoration (Teng et al., 2019).

6.3. Soil leaching

During heavy rainfall, irrigation, or recharge events, large volumes of water may come into contact with various substances as soil pore spaces fill (O'Connor and Hou, 2019). In this process, there are complex interactions between gaseous, liquid, and solid phases for soil nutrients, potentially toxic elements, and organic pollutants. If soil nutrients or contaminants are leached from surface soils, they can transport into the subsurface via the vertical migration of infiltration water. This can lead to large scale groundwater pollution involving substances such as ammonia (Jia et al., 2019). Leached nutrients in surface runoff may also enter nearby surface water bodies, causing eutrophication (Maguire and Sims, 2002). Soil leaching may be particularly prominent in the autumn-winter season due to reduced plant activity (Welten et al., 2019).

Soil leaching potential is exacerbated by common physical farming practices, including the installation of deep drainage (Nachimuthu et al., 2019). The potential for soil leaching is also affected by soil management practices that alter the chemical composition of soil. For instance, liming is a common farming method to increase soil pH and reduce flocculation. However, recent studies have suggested that soil particle surfaces become more negatively charged as soil pH increases. Therefore, liming activity may lead to soil-bound harmful substances, such as perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), leaching from soil and entering groundwater systems (Oliver et al., 2019). In New Zealand, intensified agricultural production on steep landscapes, which is encouraged by the government's policy to significantly increase agricultural exports, has involved the replacement of perennial pastures with winter forage crops. This has increased the use agrochemicals, including glyphosate and diazinon, which not only pose an environmental risk in themselves, but also facilitate the leaching of organic carbon and nitrogen (Chibuike et al., 2019). The reporting of such unintended consequences reinforces the importance of comprehensive assessments for sustainable soil use and management. It should be noted that certain soil amendments, such as biochar, have been shown to reduce soil nutrient leaching potential (Laird et al., 2010a).

Soil leaching can increase the spatial heterogeneity of soil nutrients, which makes soil management more difficult. For instance, intensively farmed cropland tends to be subject to high nitrogen input levels. However, plant-animal-soil systems are not efficient in utilizing large amounts of nitrogen, with only 15–35% being embedded in agricultural products. A large percentage of the surplus nitrogen is returned to localized spots via animal urinary excretions, resulting in elevated nitrogen hotspots.

7. Summary, challenges and future directions

The international community's commitment to achieving the United Nations' Sustainable Development Goals (SDGs) hinge on soil health. However, neither the scientific community nor policy makers have paid sufficient attention to soil in their SDG efforts. Soil scientists have not been adequately involved in the discussion on SDG targets and indicators (Bouma et al., 2019). Consequently, while there are four SDG targets that specifically mention soil, and others that indirectly relate to soil, only one explicit soil indicator has been established (Bouma et al., 2019). The lack of involvement by soil scientists may be due to their strong focus on pure soil science, rather than conducting cross-disciplinary and elaborate discussions on big picture soil related issues with other stakeholders. To help provide effective SDG solutions, it is imperative to encourage interdisciplinary soil research among soil scientists and researchers in fields relating to social science, climate science, ecology, and environmental science. When national and local governments form policies according to the United Nations SDGs, soil scientists need to be encouraged to play a more active role, and their advice needs to be sought by decision makers. For instance, by nominating soil scientists to key steering committees.

A big challenge for sustainable soil use and management is the inherent spatial heterogeneity of soil properties, from the micro to the global scale. This makes it difficult to predict non-linear relationships among various soil processes and system behaviors (Manzoni and Porporato, 2009). For example, regional estimates of soil organic carbon stocks have differed by as much as 60% on different scales due to this heterogeneity (Illiger et al., 2019). There is little known about the vertical distribution of organic carbon in the subsurface (Balesdent et al., 2018). As large amounts of carbon are stored in deep soils (Yu et al., 2019), it is essential to understand the status, as well as the mechanisms, of soil carbon cycling across the full extent of the lithosphere.

Spatial heterogeneity also exists in socioeconomic systems. Consider for example the size of typical farm holdings among different countries. In rural China, most farms are smallholdings of <0.5 ha. In Hungary, most farms are also relatively small, with 79% being <2 ha. In contrast, Danish farms tend to quite large, with 55% being larger than 20 ha (Ingram and Mills, 2019). Such differences create challenges for knowledge transfer between countries. For instance, farm size may act as a barrier to the adoption of sustainable farming technology because of financial or technical constraints (Alskaf et al., 2020).

It is important to describe long-term temporal trends in soil system behavior because many prominent issues, such as the climate crisis, require perceptive solutions based on long-term evidence. However, many existing studies, especially studies on emerging issues, are based on short-term findings. For instance, a recent pasture-system study suggested that various species could be planted to control nitrogen leaching associated with cow urine (Welten et al., 2019). This promising finding, however, was based on less than one year of data. Longer-term studies are necessary to verify the effectiveness of such strategies. Greater efforts should be paid on the research and development of accelerated aging techniques (Shen et al., 2019)

Progress in sustainable soil use and management relies upon the development of suitable and holistic indicators for soil health that reflect the diverse processes involved, in a concise, quantifiable, reliable and meaningful way. To achieve this goal, soil health needs to be evaluated under site-specific conditions that account for the different processes of different geological, climatic, and societal conditions (Vogel et al., 2018). This would be particularly valuable for aiding farmers with decision making and translating soil science into practical sustainable soil use and management practice. Moreover, to support policy making processes, it is necessary to map soil properties on a regional scale, or even on national and global scales. High resolution mapping and clustering of soil properties would enable targeted recommendations for sustainable soil management (Donoghue et al., 2019). It should also be noted that while many existing soil sustainability studies have focused on the impacts of socioeconomic activities (i.e. soil management) on soil systems (i.e. soil health), studies regarding the impacts of soil systems on socioeconomic systems are less common (Vogel et al., 2018).

Information management and knowledge sharing are critical for building collaborative governance and delivering sustainable solutions (Bodin, 2017). In this new era of information, massive amounts of valuable information (and misinformation) are produced. This poses a challenge to both the knowledge creators, who struggle to make it visible in an ocean of information, and the knowledge users, who struggle to distinguish whether information is valuable or not. Emerging and advanced technologies, such as 5G, big data and machine learning present great opportunities for addressing these challenges. Interdisciplinary studies initiated by, or in collaboration with, communication engineers and computer scientists hold much potential in advancing our capability in sustainable use and management of soil resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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