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INVITED OPINION ARTICLE

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Sustainable futures over the next decade are rooted in soil science

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Abstract

The importance of soils to society has gained increasing recognition over the past decade, with the potential to contribute to most of the United Nations' Sustainable Development Goals (SDGs). With unprecedented and growing demands for food, water and energy, there is an urgent need for a global effort to address the challenges of climate change and land degradation, whilst protecting soil as a natural resource. In this paper, we identify the contribution of soil science over the past decade to addressing gaps in our knowledge regarding major environmental challenges: climate change, food security, water security, urban development, and ecosystem functioning and biodiversity. Continuing to address knowledge gaps in soil science is essential for the achievement of the SDGs. However, with limited time and budget, it is also pertinent to identify effective

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methods of working that ensure the research carried out leads to real-world impact. Here, we suggest three strategies for the next decade of soil science, comprising a greater implementation of research into policy, interdisciplinary partnerships to evaluate function trade-offs and synergies between soils and other environmental domains, and integrating monitoring and modelling methods to ensure soil-based policies can withstand the uncertainties of the future.

Highlights

- We highlight the contributions of soil science to five major environmental challenges since 2010.
- Researchers have contributed to recommendation reports, but work is rarely translated into policy.
- Interdisciplinary work should assess trade-offs and synergies between soils and other domains.
- Integrating monitoring and modelling is key for robust and sustainable soils-based policymaking.

KEYWORDS

biodiversity, climate change, ecosystems, food security, sustainable development goals, urban development, water security

1 | INTRODUCTION

By the end of the decade, the United Nations (UN) Agenda for Sustainable Development – the 17 Sustainable Development Goals (SDGs) – are intended to be substantively realized (United Nations, 2015). Although only six SDGs mention the word "soil" in their descriptions, the importance of maintaining productive soils for sustainable development has been increasingly recognized by scientists and policymakers (Banwart, 2011; IPBES, 2018; Keesstra et al., 2016). This is largely due to the fact that soils are an essential nexus between different spheres of the terrestrial environment, facilitating a diverse array of important functions, such as producing food, purifying water, sequestering carbon, safeguarding energy, supporting critical infrastructure, providing acreage for development and supplying raw materials (Blum, 2005).

In response to an emerging need to better understand soils as key deliverers of these vital services, the make-up of the soil science research community has been transformed. Soil science has arguably shifted from a discipline largely concerned with the fundamental mechanics of soil systems (soil physics, soil biology, soil chemistry, soil hydrology, etc.), to one more focused on confronting contemporary environmental challenges (Hartemink & McBratney, 2008). The importance of, and need to understand, the components of soil systems has not been made redundant, but more and more fundamental soil science is being translated into applied "real-world" solutions.

This shift in the identity of soil science has arguably motivated soil scientists to work with a more diverse array of environmental disciplines (Hou, Bolan, Tsang, Kirkham, & O'Connor, 2020). As a result of partnering with neighbouring (and sometimes tangential) fields, soil science has become enriched with new methodological capabilities, transformed analytical techniques and more holistic solutions to address the issues of the day.

In this paper, we begin by spotlighting some of the work that soil scientists have carried out over the past decade to confront grand global challenges, including climate change, food security, water security, urban development, and ecosystem functioning and biodiversity. In each of these themes, there are still unanswered research questions and knowledge gaps, and a number of papers in recent years have sought to compile these into a manifesto for soil science (Adewope et al., 2014; Blum, 2006; Rodrigo-Comino et al., 2020). This paper does not aim to embellish these lists. With less than 10 years to go before the SDGs are intended to be achieved, and with finite resources and budget available, we believe that now is the time to consider not *what* should be researched, but *how* soil science can best ensure that the research that has been, and continues to be, carried out can support global efforts to secure sustainable development by 2030. We will suggest three "ways of working", including

(a) implementing research in policy and practice; (b) working across disciplines to evaluate function trade-offs and synergies between soils and other environmental domains; and (c) integrating monitoring and modelling methods to ensure that soils-based legislation is resilient.

2 | 2010–2020: THE CONTRIBUTIONS OF SOIL SCIENCE TO FIVE GRAND CHALLENGES

2.1 | Climate change

There is a growing recognition that soils have a crucial role in mitigating climate change, such as reducing methane and nitrous oxide emissions and sequestering carbon that would otherwise end up in the atmosphere (Paustian et al., 2016; Smith, 2012; Smith, 2016). This has led to the development of high-profile, global initiatives such as "4p1000", an international political effort launched at the 2015 COP21 summit in France to preserve and increase soil organic carbon stocks, improve food security and help tackle climate change (Chabbi et al., 2017; Rumpel et al., 2018; Soussana et al., 2019). Almost 50 governments and local authorities with hundreds of private and public sector partners are participating in this initiative.

Several studies in the past decade have sought to estimate global soil organic carbon sequestration potential. The Intergovernmental Panel on Climate Change (IPCC) recently collated these estimates (Smith et al., 2019; Smith et al., 2020a) and found the global potential for soil organic carbon sequestration to be within the range of 1.3–5.1 $GtCO_2e$ $year^{-1}$, although the full range reported in the literature is wider (0.4–8.6 $GtCO_2e$ $year^{-1}$) (Bossio et al., 2020; Fuss et al., 2018). This wide range is, in part, a reflection of the variable efficacy of different soil management practices to sequester organic carbon, and the non-linear decline of sequestration rates as fresh soil organic carbon steady state is reached (Amundson et al., 2015). In addition, there is vast potential for the sequestration of soil inorganic carbon as secondary carbonates and bi-carbonates (Lal, 2019). For instance, a recent study showed that although biochar addition can expand soil organic carbon stocks, it can also increase the dissolved inorganic carbon content in soils (Shi et al., 2020).

Cultural, economic and physical barriers constrain the capacity for soils to mitigate climate change, demonstrating the need for the soil science community to articulate the benefits of carbon sequestration in order to achieve maximum societal impact and acceptance (Amundson & Biardeau, 2018). However, accurately quantifying soil organic carbon sequestration potential is also confronted by the difficulties in monitoring, reporting and verifying (MRV) changes in soil organic carbon stocks, because these changes are relatively small and slow, and thus difficult to detect against large background stocks (Smith et al., 2020b). In the past decade, soil organic carbon MRV platforms harnessing new capabilities have been proposed. Amongst these are long- and short-term field experiments, well-calibrated models, state-of-the-art spatial datasets, spatial soil survey data, activity data and remote sensing (Smith, Soussana, et al., 2020b). Moreover, detailed MRV protocols are being developed, such as the Food and Agriculture Organisation's (FAO's) recarbonization of global soils (RECSOIL) programme (FAO, 2019a).

Measuring soil organic carbon has, until recently, generally entailed destructive sampling, soil processing, and wet chemical analysis or dry combustion. However, research in the past decade has focused on developing non-destructive methods to measure soil organic carbon both in the laboratory and in the field. These methods rely mainly on reflectance of light by the soil in the mid- (4,000–600 cm^{-1}) and near- to short-wave infrared region (2,000–2,500 nm). The concentration of soil organic carbon can be estimated from these spectral measurements by comparing them with spectral libraries derived from samples on which soil properties have been determined by traditional laboratory methods and reflectance measurements (Smith, Soussana, et al., 2020b). The ultimate aim of these innovations has been to obtain low-cost, scientifically validated, field-based tools for the non-destructive measurement of soil organic carbon (Dhawale et al., 2015; Hutengs, Ludwig, Jung, Eisele, & Vohland, 2018; Tang, Jones, & Minasny, 2019). Although these tools are helping with the determination of soil organic carbon state, further rigorous testing is required to establish their reliability in determining soil organic carbon change.

The past decade has also witnessed advances in remote sensing, by deploying unmanned aerial vehicles (UAV), aeroplanes and satellite infrastructures to detect changes in soil properties. Although these can infer changes in soil organic carbon through vegetation change, remote sensing technology that can directly measure soil organic carbon is yet to be developed (Smith, Soussana, et al., 2020b). Hyperspectral imagery can be interpreted directly in combination with spectral libraries for quantification of soil organic carbon for the top centimetre of bare soil (Gomez, Lagacherie, & Bacha, 2012; Jaber, Lant, & Al-Qinna, 2011), or by using multivariate imagery to map bare soil patterns to indicate soil organic carbon or soil class differences (Gallo et al., 2018; Rogge et al., 2018).

Furthermore, new-generation soil organic carbon models have been developed since 2010 to complement traditional models. These represent soil organic carbon turnover with pseudo first-order decay approaches with a range of soil organic carbon pools, controls on turnover times, and decomposition pathways (Smith et al., 2018). In particular, these new models include an explicit description of microbes, mineral–surface interactions, vertical transport, nutrient controls and plant interactions (Smith et al., 2018). It is unclear whether these will lead to more accurate predictions, but there are some processes for which pool-based models are unsuitable, and microbially explicit representations are required. These include soil priming (Georgiou, Koven, Riley, & Torn, 2015), microorganism mortality (Georgiou, Abramoff, Harte, Riley, & Torn, 2017), and the leaching and stabilization of dissolved organic carbon (Dwivedi, Riley, Torn, Spycher, & Maggi, 2017).

Although most of the recent research on soils and climate change has focused on climate mitigation, understanding the role of soils in climate change adaptation has also progressed. Management of soil organic carbon, erosion control, soil-borne diseases, and the prevention and reversal of topsoil salinization have been promoted as actions for climate change adaptation (Dagar, Sharma, Sharma, & Singh, 2016; Qadir, Noble, & Chartres, 2013; UNCTAD, 2011). Because these soil management measures are used to address land degradation, and because restoring degraded land helps to improve resilience to climate change, sustainable soil management has been championed as essential for climate change adaptation.

2.2 | Food security

Of the 5 billion hectares of agricultural land used for crops (1.5 billion hectares) and livestock (3.5 billion hectares), one-third of this total area is classified as degraded (FAO, 2015a). Almost 70% of total freshwater withdrawal is used for irrigation, and one-third of all anthropogenic greenhouse gas emissions are attributed to agricultural activities (Crippa et al., 2021). Global agriculture produces enough food to feed 10 billion people, yet as much as 30% of food is wasted globally (Lal, 2017). Therefore, judicious use of food, and a change in dietary preferences in favour of more plant-based diets, has been increasingly encouraged. Rather than expanding the land area under agriculture, work over the past decade has explored producing "more from less", by enhancing eco-efficiency of both soil and water, and reducing waste.

Since 2016, improved cropping systems have been studied worldwide, marking a shift from using soils as a substrate to produce food, towards a multiple-goal production system: producing food while improving soil quality. Widespread adoption of soil restorative measures to enhance soil organic carbon content and reduce erosion are critical for achieving food and nutritional security, particularly in developing countries (Evans, Quinton, Davies, Zhao, & Govers, 2020; Oliver & Gregory, 2015; Rojas, Achouri, Maroulis, & Caon, 2016; Tittonell, 2015). Over the past decade, soil science has focused on recycling biomass to build soil organic carbon content to improve soil health (Oliver & Gregory, 2015; Scharlemann, Tanner, Hiederer, & Kapos, 2014), with "soil health" here being defined as "the vitality of a soil in sustaining the socio-ecological functions of its enfolding land" following Janzen, Janzen, and Gregorich (2021), but see Baveye (2021) for a critical analysis of soil health definitions. For example, implementing zero-till farming, in conjunction with crop residue mulching and cover cropping, has been found to enhance topsoil health (Knapp & van der Heijden, 2018). Improving soil organic carbon content has also been identified conceptually to enrich soil biodiversity and human health (Wall, Nielsen, & Six, 2015), as well as increase drought resilience through enhancing green water supply (i.e., the water stored in soil and available for plant uptake) in the root zone (Marasco et al., 2012; Sposito, 2013). Transformative advancements in soil biology have demonstrated that maintaining soil organic carbon content is critical to the rhizosphere microbiome (Berendsen, Pieterse, & Bakker, 2012), which, in turn, has been shown to drive plant productivity in agroecosystems. For example, Wei et al. (2015) showed that resident soil bacterial communities can significantly reduce the invasion success of pathogens into host plants.

Recent work by Ball, Hargreaves, and Watson (2018) has shown the importance of the soil–society nexus for improving food system sustainability. Their framework, involving three types of connections, includes: (a) direct connections that enhance soil awareness for innovative management, such as organic, no-till or conservation agriculture; (b) indirect connections between soil, food and ecosystem services that can be promoted through home gardening and education (Edmondson et al., 2020; Lal, 2020a); and (c) temporal connections that draw on past usage of soil to raise awareness among policymakers (Evans, Vis, Dunning, Graham, & Isendahl, 2021).

2.3 | Water security

Over the past decade, scientists have investigated approaches to boost water use efficiency, through either plant-based interventions, which are beyond the scope of this paper, or water-management strategies. A significant advancement has been to test and develop measures to retain water within the soil by improving soil organic carbon content. Long-established techniques such as mulching and cover cropping (Li, Zhao, Gao, Ren, & Wu, 2018; Wheeler & Marning, 2019) have been complemented with innovations such as using wetting agents (e.g., surfactants) and wax-degrading bacteria to reduce soil water-repellence (Saji, 2020), and developing soil conditioners composed from natural (e.g., cellulose, starch, yeast, chitosan) and biodegradable waste products (Saha, Rattan, Sekharan, & Manna, 2020). Although these novel advancements have been trialled, continued investment is required to validate their effectiveness across a wider array of land-use and climatic contexts.

Groundwater depletion is a rapidly increasing problem globally (Hohne, Esterhuyse, Fourie, Gericke, & Esterhuyse, 2020). To meet increasing demand, several strategies have been developed over the past decade to efficiently manage groundwater conditions (Chatterjee et al., 2020). Artificial groundwater recharge has been performed through water harvesting structures, by collecting surface runoff, and increasing infiltration through a combination of dry wells, percolation tanks and/or bank infiltration recharge, while preventing water-quality decrease (Ahirwar, Malik, Ahirwar, & Shukla, 2020; Sandoval & Tiburan, 2019). This has been upscaled by the deployment of remote sensing and geographic information system (GIS) techniques to precisely identify suitable sites to enhance groundwater recharge potential, through analysing relevant factors such as geomorphology, geology, slopes, land use and drainage characteristics (Chandra, Singh, Tiwari, Panigrahy, & Kumar, 2015; Khan, Govil, Taloor, & Kumar, 2020; Machiwal, Jha, & Mal, 2011). Remote sensing has also been used to detect terrestrial water cycling through the detection of changes in Earth's gravitational field (Feng, Shurn, Zhong, & Pan, 2018; Rodell et al., 2007). These data monitoring efforts are essential for ensuring the efficient management of groundwater recharge, and to avoid the failure of aquifer systems.

Quantifying spatiotemporal variations in green and blue water is a mainstay of ensuring water security. Here, 'blue water' is defined as the proportion of water resources stored in rivers, lakes and groundwater that is directly available to humans, whereas "green water" is the water stored in soil and available for plant uptake, following Menzel and Matovelle (2010). Over the past decade, soil scientists have capitalized on major advances in data acquisition and modelling to make an inventory of the spatial distribution of the planet's water supply (Chawla, Karthikeyan, & Mishra, 2020; Obade & Moore, 2018). With these data, and the development of models that link hydrological processes with other environmental, social and economic factors, soil scientists are now better equipped to investigate and quantify water security in terms of scarcity and vulnerability (Bagheri & Babaeian, 2020), and to support integrated water resource management from a holistic perspective (Babel, Pandey, Rivas, & Wahid, 2011; Mahdavi, Bagheri, & Hosseini, 2019). This data revolution has catalysed the development of several machine learning methods that can forecast the effect of environmental and climate change on future water and pollutant fluxes (Morellos et al., 2016; Yamaç, Şeker, & Negiş, 2020). In addition, soil scientists are working more closely with critical zone scientists to advance current understanding of subsurface water stocks and dynamics (Hahm et al., 2019). For example, recent developments in ground-based gradiometry now allow for more accurate monitoring of subsurface structures and their associated water storage (Parsekian, Singha, Minsley, Holbrook, & Slater, 2014). As well as these technological advancements, the introduction of simplified water indices to indicate water scarcity (Chawla et al., 2020; Veettil & Mishra, 2016) has made it possible for both policymakers and public stakeholders to better understand the need to pay greater attention to water security in the future (Babel, Shinde, Sharma, & Dang, 2020).

2.4 | Urban development

Over the past decade, issues relating to, or originating from, urban soils have been addressed in various assessments, resulting in the development and implementation of different innovations, technologies and strategies (Barthel et al., 2019; Biasi, Colantoni, Ferrara, Ranalli, & Salvati, 2015; European Commission, 2015; Salvati, Zambon, Chelli, & Serra, 2018). There has been a rapidly increasing interest in urban soils, such as through the activity of the "Soils of Urban, Industrial, Traffic and Mining Areas (SUITMA) working group" (Burghardt, Morel, & Zhang, G-.L., 2015). By assessing the state of urban soils, soil scientists have conceived various strategies to improve soil structure and enhance water infiltration and retention (Kalantari, Ferreira, Keesstra, & Destouni, 2018; Kumar & Hundal, 2016). These include traditional strategies such as tillage to alleviate soil compaction (Environmental Protection Agency, 2011), and more state-of-the-art approaches such as bioremediation to decrease soil contamination and enhance soil biodiversity (Environmental Protection Agency, 2011; Sarwar et al., 2017). The application of soil amendments, such as compost, and the installation of blue-green infrastructures has also been tried (Kumar & Hundal, 2016). Blue-green infrastructure is a multifunctional network of natural and designed areas, comprising water bodies, green spaces and open spaces (Ghofrani, Sposito, & Faggian, 2017). Yet, all of these remediation and restoration strategies bring some challenges. For instance, the excavation and removal of contaminated soil can be highly or even prohibitively expensive, especially if required over a large area.

Nature-based solutions (NBS) are now being widely adopted to specifically address decades of unsustainable spatial planning policies in urban areas (European Commission, 2015; Pan et al., 2018). Mitigating soil degradation in urban environments using NBS is both innovative (Goldenberg, Kalantari, & Destouni, 2018; Kalantari, Ferreira, Deal, & Destouni, 2019a) and also cost-effective, and it simultaneously provides environmental, social and economic benefits that can help achieve numerous SDGs (European Commission, 2015; Jaramillo et al., 2020; Seifollahi-Aghmiuni, Nockrach, & Kalantari, 2019). For example, street trees, parks and wetlands have been shown to intercept dust and toxins, sequester carbon (Jonsson, Page, & Kalantari, 2019), buffer flooding and prevent soil degradation (Jaramillo et al., 2020). In addition, straw mulches (Rodrigo-Comino et al., 2019), vegetative filter strips (Pan et al., 2018) and natural vegetation covers (e.g., green roofs and walls) are important NBS that reduce storm-water runoff and prevent soil erosion in urban areas. Technosols constructed from city waste, such as compost or chipped wood, provide many ecosystem services and contribute to circular economies (Grard et al., 2018).

Demonstrating the benefits of NBS in urban environments through proof-of-concept experiments is critical for underpinning their inclusion in urban planning (Kalantari et al., 2019b). Once implemented, their continuous maintenance requires long-term labour inputs, mostly at the community level (Ferreira, Walsh, Blake, Kikuchi, & Ferreira, 2017). Because soils are central to supporting many urban NBS, soil scientists are beginning to enjoy increasing levels of engagement in urban planning, and are working alongside stakeholders, local communities, authorities, architects and construction companies to ensure that soils are sustainably managed and preserved in urban environments (Keesstra et al., 2016).

2.5 | Ecosystem functioning and biodiversity

Over the past decade, the soil science community has transferred an understanding of soils into natural capital and ecosystem service frameworks (Dominati, Patterson, & Mackay, 2010; Haines-Young & Potschin, 2012; Robinson, Lebron, & Vereecken, 2009). One of these frameworks is the System of Environmental and Economic Accounts (SEEA) (Obst, Hein, & Edens, 2016; United Nations, 2012a), which, by providing satellite green accounts alongside Gross Domestic Product (GDP) accounts (United Nations, 2012a), considers the soil as one of seven natural resources. The added value these frameworks bring to GDP accounting is the recognition that natural resources are not free or limitless, and that they can constrain the economy, if not carefully managed. Yet, some have argued that combining data on soil resources with natural capital and economic activity indicators is one of the least developed areas of the SEEA, which has led to more efforts from soil scientists to address this gap over the past decade (Obst, 2015).

Adopting a systems approach emphasizes the importance of monitoring multiple ecosystem cycles to underpin reporting frameworks, including soil formation and erosion, soil carbon gains and losses, soil nutrient release and loss, and soil water and energy balance (Amundson et al., 2015; Robinson et al., 2017). Advances in both modelling (Borrelli et al., 2017) and monitoring (Panagos, Meusburger, Ballabio, Borrelli, & Alewell, 2014) over the past decade have rendered this approach feasible. They have also demonstrated a way forward for addressing one of the key challenges identified in the Intergovernmental Technical Panel on Soils (ITPS) report: the need for "state" and "trend" monitoring of soils (ITPS, 2015). Although the development of an SEEA-style soil monitoring and modelling framework is an end in itself for policymaking, it is also important for providing an understanding of soil change.

Accounting for change in soil biodiversity and function remains a substantial challenge in soil science, yet has received significant investment over the past decade. Due to the large variety of soil organisms, ranging from microorganisms to invertebrates and vertebrates, surveys on soil biodiversity require specific tools and methods depending on which group of organisms is studied. Transformative advances in omics have revealed the breadth and distribution of organisms in soils (Prosser, 2015), which are vital for ecosystem functioning (Crowther et al., 2019; Delgado-Baquerizo et al., 2018), and their development in soil science represents a major achievement.

Over the past decade, sequencing and informatics technologies have forged ahead, such that the retrieval of full genomes of previously unknown soil organisms is now becoming more common (Nesme et al., 2016). However, the contribution of soil organisms to health and well-being services has often been overlooked. Most antibiotics in use today were extracted from soil organisms in the 1940s-60s (Lewis, 2013), and the first new antibiotic to be identified for decades was recently extracted from soil (Ling et al., 2015).

Innovations in technology are therefore prompting scientists to revisit soils for biomedical and biotechnological resources (Lewis, 2012), and molecular technologies, which uncover previously unknown soil microbial species and functions, provide many new opportunities in this regard (Hover et al., 2018). More generally, these technologies allow for a better appreciation of the specific mechanistic roles of soil biodiversity in regulating wider ecosystem services such as nutrient recycling and storage (Hartman, Ye, Horwath, & Tringe, 2017), greenhouse gas regulation (Hester et al., 2018) and plant productivity (Carrión et al., 2019). Linking soil biodiversity to a natural capital framework is therefore fundamentally important, and remains to be achieved, in SEEA. Significant challenges remain in how to assimilate the vast amounts of globally obtained molecular information, and experimentally determined ecological interactions between organisms, into both soil process and wider ecosystem service models. Here, advances in digital technologies for biodiversity data synthesis (Choi et al., 2016), modelling and dissemination (Větrovský et al., 2020), coupled with detailed biogeochemical investigation of the functional relevance of new genes under environmental change contexts, provide much scope for future exploration and discovery. In concert, a better understanding of how soil biodiversity interacts to deliver multiple ecosystem benefits, win-wins and trade-offs, offers the potential for new ways to both monitor soil health and also move towards more sustainable approaches to manage and optimize soil multifunctionality in the face of environmental change (Rillig et al., 2019).

Ecosystem service models continue to progress (Bagstad, Semmens, Waage, & Winthrop, 2013), but the incorporation of soil functions and feedbacks remains an area warranting further attention if we are to better understand the impacts of land use, pollution and climate change. Recent work has improved the understanding of linkages between soil attributes, functions and ecosystem service provision (Adhikari & Hartemink, 2016). However, incorporating this understanding into ecosystem service modelling has been slow. Some have pointed out that the majority of ecosystem service models only account for a single soil function (Greiner, Keller, Grêt-Regamey, & Papritz, 2017). Failing to represent multiple functions of soil is a weakness given that a key role of ecosystem service models is to account for multiple services, and understand their relationships, trade-offs and synergies. Recent work has attempted to address this, such as the Soil QUality InDex (SQUID), which assesses the provision of 16 different soil-based ecosystem services (Drobnik, Schwaab, & Grêt-Regamey, 2020), soil function assessment methods (Greiner et al., 2017) and the Soil Navigator decision support system (Debeljak et al., 2019). However, most of the more widely used models fail to appropriately incorporate benefits from soils or soil degradation processes, while low availability of spatial soil data often leads to land cover data being used as a proxy (Adhikari & Hartemink, 2016). Although biophysical information is informative in itself, translating changes in resources into economic impacts is an important goal for natural capital accounting, yet to be achieved.

Attempts have been made to account for economic costs at the national scale (e.g., Graves et al., 2015), which tend to rely on first-order cost evaluation. However, recent work has tried to use models to link soil degradation to the global economy (Sartori et al., 2019). This work goes "beyond the use of 'first-order' cost evaluation and captures the 'second-round' effects of structural economic change that arise owing to shifts in primary resources, particularly the land factor" (Sartori et al., 2019). It provides proof of concept for realising a full benefit chain, from soil monitoring and modelling, through to economic impact assessment.

3 | TOWARDS 2030: AN INTEGRATED AGENDA FOR SUSTAINABILITY

There are less than 10 years to go before the SDGs are intended to be achieved. At this critical juncture, it is pivotal to step back and analyse the work that soil scientists should do to contribute towards the realization of these goals. There have been a number of papers in recent years that have synthesized the research questions left outstanding in soil science and made calls to the community to tackle them (Adewope et al., 2014; Blum, 2006; Rodrigo-Comino et al., 2020). These have been useful for prescribing research agendas, justifying research rationale, and securing funding for new highlight topics and foci areas. As important as this process is, we argue that it cannot catalyse real-world impact alone. Therefore, in this section of the paper, we do not suggest *which* specific topics soil scientists should research next, but begin an important dialogue around *how* soil scientists can best ensure that their research over the next decade can best support global efforts to secure sustainable development by 2030.

3.1 | Implementing research in policy and practice

This paper has summarized the research advances made over the past decade in soil science with respect to five critical areas. It is important to ask how this research has been utilized to drive sustainable development. Figure 1 presents a timeline of some of the global initiatives towards which soil scientists have contributed over the past decade. These can be divided crudely into four categories: (a) guidance documents and recommendations; (b) status reports; (c) expert group collaborations and public

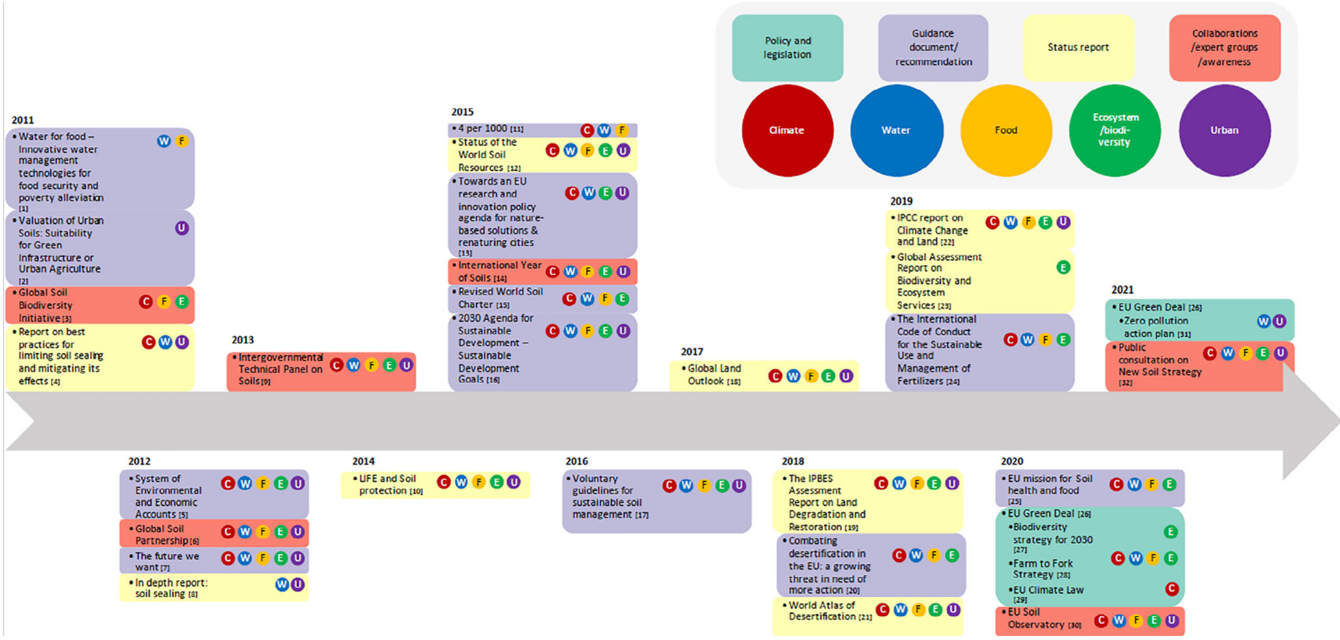

FIGURE 1 Timeline highlighting contributions of soil science to international policy and legislation, guidance and recommendation reports, status reports, and collaboration and public awareness campaigns across five major environmental challenges over the past decade. (1) United Nations Conference on Trade and Development, 2011; (2) Environmental Protection Agency, 2011; (3) Global Soil Biodiversity Initiative, 2021; (4) European Commission, 2011; (5) United Nations, 2012a; (6) Food and Agriculture Organisation (FAO), 2012; (7) United Nations, 2012b; (8) European Commission, 2012; (9) FAO, ; (10) European Union, 2014; (11) 4 Per 1000, 2021; (12) FAO, 2015a; (13) European Commission, 2015; (14) FAO, 2015b; (15) FAO, 2015c; (16) United Nations, 2015; (17) FAO, 2016; (18) United Nations Convention to Combat Desertification, 2017; (19) Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2018; (20) European Court of Auditors, 2018; (21) European Commission, 2018; (22) Intergovernmental Panel on Climate Change (IPCC), 2019; (23) Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019; (24) FAO, 2019b; (25) European Union, 2020; (26) European Commission, 2019; (27) European Commission, 2020a; (28) European Commission, 2020b; (29) European Commission, 2020c; (30) European Commission, 2021a; (31) European Commission, 2021b; (32) European Commission, 2021c [Color figure can be viewed at wileyonlinelibrary.com]

awareness campaigns; and (d) policy and legislation. It demonstrates that the majority of activities have either focused on compiling evidence for reports on the state of the world's soils, or making recommendations on how best to manage and conserve them. Although these types of publications are important for conveying the outcomes of scientific research, their capacity to manifest real-world impact is relatively weak in comparison to concrete policy and legislation, of which there are very few examples to highlight.

Effective translation of research into concrete legislation is essential for achieving sustainable development by 2030. Catalysing action requires a national or regional action plan, which reconciles local/national policy agendas and global assessments. An example of this is the new European Green Deal, which represents an ideal opportunity for soil scientists to directly influence the policy agenda, as the European Commission aspires to make the EU the first climate-neutral continent by 2050 through implementing a "Climate Law" (Figure 1) (Montanarella & Panagos, 2021). In order to comply, it is likely that Member States will also conceive and implement national policies over the next decade. This highlights the need to promote closer and more sustained working relationships between soil scientists and policymakers at national and international levels.

Effective partnerships between soil scientists and policymakers cannot be manifested overnight, but the response to the COVID-19 pandemic, at the very least, demonstrated that science-informed policies can be tabled and implemented efficiently if a significant impetus is present. It therefore seems incumbent that soil scientists will need to tailor their approach to convey urgency and capture the attention of policymakers (Lal, 2020b). Although the publication of status reports and guidance documents can support this, it is also worthwhile to consider recent examples of environmental legislation. In the case of reducing plastic pollution, for example, the development of UK legislation, in part, followed an outreach documentary film and similar public engagement activities. These were largely spearheaded by non-scientist individuals with a sizeable public following, working closely with scientists (Davison et al., 2021). The question for the next decade, therefore, is to whom should soil scientists turn to stimulate public consciousness about the challenges facing soil resources and the importance of sustainable soil management?

3.2 | Integrating research agendas

Agenda 2030 comprises goals for the biosphere, societies and their economies. Achieving (and perhaps more importantly, continuing to achieve) all 17 of the SDGs is a large task, but arguably the greatest challenge is coordinating action so that the delivery plans for one goal do not outcompete or nullify the potential to achieve others. Recently, research has examined the trade-offs and synergies between the SDGs, whether some goals act as prerequisites for others, and how perceived trade-offs can be transformed into virtuous cycles of sustainable development (Kroll, Warchold, & Pradhan, 2019; Scherer et al., 2018; Singh et al., 2018).

Throughout the decade, there will be more lessons to learn about the ways to identify and convert trade-offs to synergies, and these should inspire new ways of collaborating within and beyond soil science. With limited time and resources allocated to soil science departments, the first step here is to develop new and efficient methods to monitor and evaluate the trade-offs and synergies between functions across soil and other terrestrial/marine systems. A seemingly minor but important shift in our future nexus thinking here is a move from considering "soil functions" or "soil ecosystem services" to acknowledging that life depends on an array of functions and services that are delivered by an integrated terrestrial–marine ecosystem, of which soil is a vital part. This perspective shifts away from one focused on delivering all ecosystem functions and services in soils simultaneously, to one which considers how these are delivered across the wider terrestrial environment. For example, urban food grown using novel (soil-less) growing techniques (e.g., soil simulants, hydroponics, bioarchitecture) may help lessen the burden on soils to deliver on growing food demands and allow those most degraded to undergo extensive restoration treatment. The essential step, therefore, is to establish the role of soils in the wider ecosystem, which will require sustained collaboration between soil scientists and the wider environmental sciences.

The infrastructure to accommodate these more strategic and collaborative networks has started to be developed (see Figure 1). On the ground, for example, Critical Zone Observatories (CZOs) host international and multidisciplinary expertise that encompass atmospheric, soil, ecological, biological, hydrological and geological sciences (Banwart, 2011). Likewise, light houses and living laboratories (Evans, 2021) have also been established to better connect innovation, practitioners and scientists. More broadly, open cloud infrastructure has enabled researchers to share methods, training resources, data analysis toolkits and associated computer codes (Blair et al., 2019). Moreover, open access publishing has enabled greater availability, accessibility and transparency of research outputs (Laakso et al., 2011). Supplementing these initiatives has been the development of publicly available global databases that not only allow researchers to share data, but standardize them for the benefit of the wider community (Benaud et al., 2020).

3.3 | Reactive and proactive soil science

Ultimately the SDGs, the European Green Deal and environmental targets at the national level are both reactive and proactive programmes for the future. They are reactive in the sense that they each acknowledge current challenges, shortfalls, disequilibria and inequalities, and seek to rectify these issues. They are also proactive because they consider how these pressures and demands will evolve over time. If soil science is to support and help achieve these national and international agenda, it is vital that researchers are armed with both a reactive and proactive strategy. In essence, this entails a balanced approach between responding reactively to existing challenges (e.g., monitoring and restoring degraded soils) and developing the foresight to predict how soils may respond to future perturbations (e.g., climate change). In practice, a critical objective is to link communities in monitoring and modelling across soil science.

The relationship between empirical and model-derived data should be considered as symbiotic. The inevitable spatial and temporal limitations of observational data indicate a need for model data, whereas empirical data are crucial to both model development and validation. Both observations and models are required to understand and quantify the current state of the soil system, and to forecast future trajectories and magnitudes of soil change (Robinson, 2015) in order to inform planning and mitigation measures (or state and trend monitoring). This challenge is highlighted in previous sections of this paper in relation to MRV difficulties and the attempts to overcome such issues through combining heterogeneous empirical and model datasets. Addressing this challenge is critical to ensure that the contribution of soils to sustaining Earth system functions is accounted for, and weaknesses in Earth system models are identified (Fatichi et al., 2020). More fundamentally, it is required for furthering scientific advancement of our understanding of the soil system, such as feedbacks (Robinson et al., 2019).

Another challenge will be to generate effective and harmonized map products. Recent advances in cloud computing provide huge potential to address this challenge (Hollaway et al., 2020), including greater data storage and discovery, additional computational capacities for model development, and coupling and uncertainty analyses. Integration of datasets creates the potential for geostatistical and machine learning approaches in relation to water and pollution, urban planning and other environmental disciplines (Avanzi et al., 2019; Padarian & McBratney, 2020). It also provides the basis for multi-goals research, such as developing cropping systems that boost food production, improving soil quality, storing carbon in soils, and reducing the use of pesticides. By linking monitoring and modelling in soil science in this way, we can both react to the present-day demands placed on soils and scope out the challenges of the future.

4 | CONCLUSION

Over the past decade, the importance of soils for realising the United Nations' Sustainable Development Goals has been widely demonstrated. Soil scientists have increasingly foregrounded the roles that soils play in combatting grand global challenges such as climate change, food and water security, urban development and ecosystem functioning, and have acknowledged their connectedness. These challenges place strong pressures on the long-term health and functioning of the biosphere. In spite of advancements in the past decade, there still remains a large number of knowledge gaps and research questions. In this paper, we have not set out an itinerary of questions for further research, rather we have argued for three ways of working that will best support global efforts to secure sustainable development by 2030. Implementing research into policy and practice is a key, yet so far under-achieved, objective. Clearly, much of this depends on the actions of policymakers, but soil scientists should acknowledge their responsibility over the next decade to build strategic relationships with them in order to support policy delivery, whilst considering innovative ways of engaging public consciousness about the challenges facing soils. It is also important that soils-based policies are sufficiently coordinated with those in other environmental domains. Here we suggest that specific collaborations between soil scientists and other disciplines to evaluate the trade-offs and synergies between soils and the wider environment are key. Finally, if policies for the future are to be built, it is important that soil scientists consider how soils will change and what issues they will face over time. Modelling can assist with this, and thus it is also vital to sustain and enhance soil monitoring programmes, on which the foundations of our models are based.

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CONFLICT OF INTEREST

There are no conflicts of interest associated with this manuscript.

DATA AVAILABILITY STATEMENT

There are no data associated with this manuscript.

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