Soil Advances 4 (2025) 100057

Contents lists available at ScienceDirect

Soil Advances

journal homepage: www.sciencedirect.com/journal/soil-advances

Enhancing “4 per 1000” initiative implementation through region-specific agricultural and forestry practices

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ARTICLE INFO

Keywords:
Soil health
Food security
Soil organic carbon sequestration
Climate change
Management practice
Forests
Agriculture

ABSTRACT

The critical importance of enhancing and maintaining the organic carbon (C) content in agricultural and forest soils has been emphasized for a decade within the objectives of the International "4 per 1000" Initiative. The multiple benefits of soil organic C (SOC) sequestration in addressing global challenges—such as food security, climate change mitigation and adaptation, and biodiversity conservation—are now well-recognized. However, less well understood is how the capacity for SOC sequestration varies across regions and what specific management practices are most suitable for promoting soil health and SOC sequestration regarding different regional contexts and initial conditions. In this paper, we review data and research from three major global regions—Africa, Asia, and Oceania—each with distinct cultural, socio-economic, and environmental challenges and opportunities. To provide insights from forest and agricultural management approaches in each region, we discuss practices that have proven effective and propose that a deeper exploration of region-specific management could lead to the identification of additional viable practices that enhance SOC sequestration. This approach would support the objectives of the "4 per 1000" Initiative and contribute to achieving global climate change and sustainable development goals.

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https://doi.org/10.1016/j.soilad.2025.100057

Available online 31 May 2025

1. Introduction

In December 2015 during the 21st COP of the UNFCCC held in Paris, France, the International "4 per 1000" Initiative 'Soils for Food Security and Climate',[2], was launched. The initiative aims to highlight the crucial role of agricultural and forest soils in promoting food security, mitigating climate change through soil organic carbon (SOC) sequestration, enhancing adaptation and resilience to the harmful effects of global climate warming, and restoring soil, land and ecosystem health, and biodiversity for better life on Earth. The "4 per 1000" Initiative is guided by an ambitious strategic plan towards 2050 through a 2030 vision comprising six goals and 24 objectives. Today, soils are receiving more political and scientific attention, due to their essential and multifaceted role in combating and adapting to climate warming and enabling human and ecosystem health i.e., fostering healthy people in a healthy environment (e.g., Rumpel et al., 2022). The special role of soil health as a central lever in climate action in agrifood systems was further recognized in the *Emirates declaration on sustainable agriculture, resilient food systems and climate* action,[3] which was adopted during UNFCCC COP28 in 2023.

At COP 22 in Marrakech (Morocco), the "4 per 1000" Initiative established a Scientific and Technical Committee (STC) composed of 14 experts from different countries and regions. The STC works to provide guidance for policymakers and contributes to the scientific debates around soil health and SOC sequestration. So far, the STC's scientific activities have included: (i) Identifying eight steps able to increase the amount of SOC worldwide in line with the Initiative's objectives along with research priorities for region-specific practices (Rumpel et al., 2018) and overcoming barriers to maintaining SOC stocks and the benefits for soil health, climate change mitigation, adaptation and resilience, and offset greenhouse gas (GHG) emissions (Rumpel et al., 2019); (ii) analysing the risks and trade-offs associated with SOC sequestration (Rumpel et al., 2023b), and (iii) contributions to encouraging collaboration between multiple parties (policymakers, practitioners, scientists, and stakeholders) of the Initiative to engage in jointly exploring solutions (Rumpel et al., 2019).

The STC contends that fostering healthy and C-rich soils, enables outcomes such as bolstering the resilience of human societies to pandemics and other crises (Rumpel et al., 2022). Hence, the "4 per 1000" Initiative advocates for sustainable practices worldwide to conserve or augment SOC stocks. Approaches must be tailored to the unique characteristics of regions, soil types, and socio-economic contexts to meet the objectives of the "4 per 1000" Initiative (Rumpel et al., 2019, 2023a; Soussana et al., 2019). In this regard, the STC elaborated a Topical Collection of 20 articles from diverse regions worldwide, highlighting the effects of sustainable management practices in agricultural and forest systems on SOC sequestration, emphasizing the importance of regional specificity (Rumpel et al., 2023a).

In light of the Initiative's 10th anniversary, the objectives of this paper are: (i) to shed light on the SOC sequestration potential of various regions and ecosystems as well as efforts and recent insights regarding successful management approaches, related to the aims of the "4 per 1000" Initiative; (ii) to highlight the importance of considering the regional specificities for implementation of the objectives of the Initiative, especially where local populations rely strongly on natural resources (often in harsh climatic conditions), and where opportunities for actions to increase SOC storage are more constrained by socio-economic or ecological aspects; and (iii) to highlight some of the vulnerable ecosystems, e.g., tropical forests and peatlands, that harbor enormous and often irrecoverable C stocks in soil and biomass (Pan et al., 2011; Goldstein et al., 2020), which are crucial for global climate regulation (Artaxo et al., 2022) and provide essential ecosystem services for the local population (Lescuyer et al., 2009; Brandon, 2014).

We discuss how the regions selected show distinct potential for SOC sequestration and favor development of specific strategies for sequestering SOC to meet the objectives of the "4 per 1000" Initiative. We will consider three main aspects: 1) Land-use and regional context for SOC sequestration; 2) Practices with potential to foster SOC sequestration, and 3) Other factors affecting the potential for sequestration.

2. Results: regional analysis

This paper focuses on Africa, Asia and Oceania, and a regional analysis of Europe, North as well as South America is envisaged to follow. Especially Africa and Asia are experiencing a rapid transition in terms of demography and consequently land use changes, which makes the implementation of sustainable practices in these regions a priority. There are large differences between these regions and each has high internal diversity. The data and case studies discussed are not intended to comprehensively represent each region but to illustrate how specific biophysical and socio-economic circumstances may support and influence effective activities to foster soil health and SOC storage. Attention was paid to selecting countries, ecosystems or communities with emerging or locally challenging economic and/or biophysical circumstances. Hence, they are areas susceptible to the impacts of climate and land-use changes, where tailored interventions are imperative (Chancel et al., 2023).

2.1. Africa

2.1.1. Central African Tropical Forest Ecosystems

2.1.1.1. Land-use and regional context for SOC sequestration. Forest ecosystems contain over 80 % of all terrestrial aboveground C and 70 % of all SOC (Jandl et al., 2006). Of the world's total forest area, over 50 % is located in the tropics, i.e., 45 % in the tropical and 11 % in subtropical climate zone, whereas 27 % is located in boreal and 16 % in temperate climate zone (FAO, 2020). Modelled fluxes using the Orbiting Carbon Observatory-2 (OCO-2) data from 2014 to 2017 show increased CO_2 fluxes across all the largest tropical rainforest regions (Eldering et al., 2017).

The Congo Basin rainforest ecosystem comprises parts of Cameroon, Central African Republic, Democratic Republic of the Congo, Equatorial Guinea, Gabon, and Republic of the Congo. With an area of approximately 2400,000 km^2, it is the world's second largest rainforest ecosystem after the Amazon (5500,000 km^2), and includes large areas of C-rich peatlands (Dargie et al., 2017). Over three decades to 2015 African tropical forest carbon sink had a higher net annual carbon dioxide equivalent (CO_2e) (-0.61 Gt CO_2e per year) than the Amazon (-0.10 Gt CO_2e per year) while, in contrast, South East Asia is currently a net CO_2e source (+0.49 Gt CO_2e per year) (Hubau et al., 2020).

Despite the rate of deforestation in the Central African region being the lowest of the world's rainforests for the period from 1990 to 2010, high deforestation rates over the last decade (FAO, 2016) now threaten the world's second largest rainforest ecosystem. The greatest annual rate of net forest loss between 2010 and 2020, i.e., 3.9 million hectares, had been recorded in Africa, followed by South America, i.e., 2.6 million ha (FAO UNEP, 2020). The increased deforestation rate in the Congo Basin is due to agricultural and/or industrial activities (FAO, 2016), particularly slash-and-burn, and high wood consumption (wood and fuel energy) (Shure et al., 2012; Eba'a Atyi et al., 2022). This endangers local communities who are reliant on forest products (including non-timber products) and other ecosystem services (Lescuyer et al., 2009; Asaah et al., 2011). Overall development threats make this region, and their high SOC sequestration potential relative to the Amazon and Southeast Asia (Hubau et al., 2020), very vulnerable to climate and land-use changes (Beekmann et al., 2024).

[2] https://www.4p1000.org

[3] https://www.cop28.com/en/food-and-agriculture

2.1.1.2. Practices with potential to foster SOC sequestration. Despite its high potential to sequester SOC mainly through forest ecosystems, the Congo Basin has been the least studied regarding climate change prospective and biodiversity of the world's three largest rainforest ecosystems (White et al., 2021; Beekmann et al., 2024). Enhancing SOC storage through forest management and/or plantations and agroforestry systems may be one of the solutions meeting the UN Agenda 2030 for Sustainable Development (particularly SDGs 3, 7, 12, 13 and 15) while also meeting the objectives of the "4 per 1000" Initiative. The area of forest plantations in Central Africa is estimated to be around 632,000 ha with Rwanda having 301,500 ha, Burundi 146,000 ha and the Republic of the Congo 74,500 ha (Eba'a Atyi et al., 2022).

However, during the forestation process, preference must be given to native species as some exotic species such as *Acacia mangium* Willd. have the potential to cause major negative impacts on biodiversity and ecosystem functioning as they may become invasive (Koutika and Richardson, 2019). Other barriers to forestation in some parts of the region (e.g. coastal Congolese plains see below) are socio-economical due to the weak involvement of the local communities, which endangers these forest plantations through harvest to satisfy demand for fuel, since over 90 % of households in main countries of the region use fuel wood for energy (Shure et al., 2012). The involvement of local communities in the afforestation and reforestation process, as already happening in some regions of Asia (Yamanoshita and Amano, 2012), is therefore crucial, and is also one of the solutions to sustain these plantations and natural forests.

To sustain and better understand the Congo Basin ecosystems, several initiatives have been created over the last decades, amongst them three new dedicated initiatives: the Science Panel for the Congo Basin (SPCB) (https://www.spcongobasin.org/), the Congo Basin Science Initiative (CBSI) (https://congobasinscience.net/), and the One Forest Vision initiative (OneForestVision). Inspired by the Science Panel for the Amazon (https://www.unsdsn.org/our-work/science-panel-for-the-amazon/), the SPCB aims to synthesize existing knowledge and identify research gaps on the status of, and threats to, the Congo Basin, its forests and related ecosystems. The ultimate goal of SPCB is to establish an assessment report to be presented at UNFCCC COP 30 in 2025. The identification of the gaps will be investigated by the CBSI and OFVi, which aim to develop an integrated understanding of the Congo Basin in a changing Earth system. All those initiatives are solutions promoting climate and land-use sensitive resilience approaches for sustainable development in the region.(Fig. 1)

Practices using trees as agroforestry systems, afforestation and /or reforestation are the most appropriate for sequestering SOC in the region (Bisiaux et al., 2009; Mbow et al., 2014; Cardinael et al., 2018; Koutika et al., 2021). Mixed-species stands with preference given to native species bring multiple benefits. In mixed-species stands with exotic species (nitrogen fixing species (NFS) and non-NFS) stand wood biomass increased relative to monocultures of NFS or non-NFS (Epron et al., 2013). Soil health also improved in mixed-species stands or agroforestry systems using NFS, including higher C and N stocks (Fig. 2, Koutika et al., 2014; Koutika and Mareschal, 2017; Tchichelle et al., 2017; Koutika et al., 2021), enhanced P dynamics in forest floors relative to non-NFS (Koutika et al., 2020a) or native savannahs (Koutika and Mareschal, 2017), and enhanced bacterial and fungal community structure and diversity in mixed-species stands (Koutika et al., 2020b; 2024).

Other important benefits of mixed-species stands are improvement of livelihood, increase in crop yields and incomes, increase of availability of fuel energy (Fig. 2, Bisiaux et al., 2009; Lescuyer et al., 2009; Shure et al., 2012, Koutika et al., 2022), highlighting the link between the benefits of those practices and the "4 per 1000"objectives (Koutika et al., 2021).

2.1.1.3. Factors affecting the potential for sequestration. There are barely any studies on socio-economic factors influencing identified best practices in the region, and SOC sequestration in particular, e.g. for forest restoration initiatives involving local populations in Central Africa (Peroches et al., 2025). However, socioeconomic barriers to SOC sequestration improvement have been identified that apply broadly to developing or low-income countries in sub-Saharan Africa including countries of Central Africa (Demenois et al., 2020 cited in Koutika et al., 2023). Efforts must be made to overcome these socioeconomic constraints in order to improve the implementation of the 4p1000 initiative and others such as SPCB, CBSI and OVFi to strengthen the potential of sequestering SOC in the region. In addition, the effectiveness of soil carbon monitoring, reporting and verification (MRV) crucial to assess SOC changes and GHG emissions/removals and enhance the potential of SOC sequestration need to be strenghtened (Koutika et al., 2025).

2.1.2. Sahel Ecosystems

2.1.2.1. Land-use and regional context for SOC sequestration. The Sahel is a vast semi-arid region across Africa, between the Sahara Desert to the north and the Sudanian Savannah to the south. It stretches approximately 5400 km (3360 miles) from the Atlantic Ocean in the west to the Red Sea in the east, covering parts of countries such as Senegal, Mauritania, Mali, Niger, Chad, Sudan, Eritrea, and Ethiopia (Foley et al., 2003; Sinare and Gordon, 2015).

The Sahel ecosystems are characterized by a unique blend of ecological, climatic, and cultural features, making them a vital and dynamic part of Africa's landscape (Sinare et al., 2022). The Sahel region,

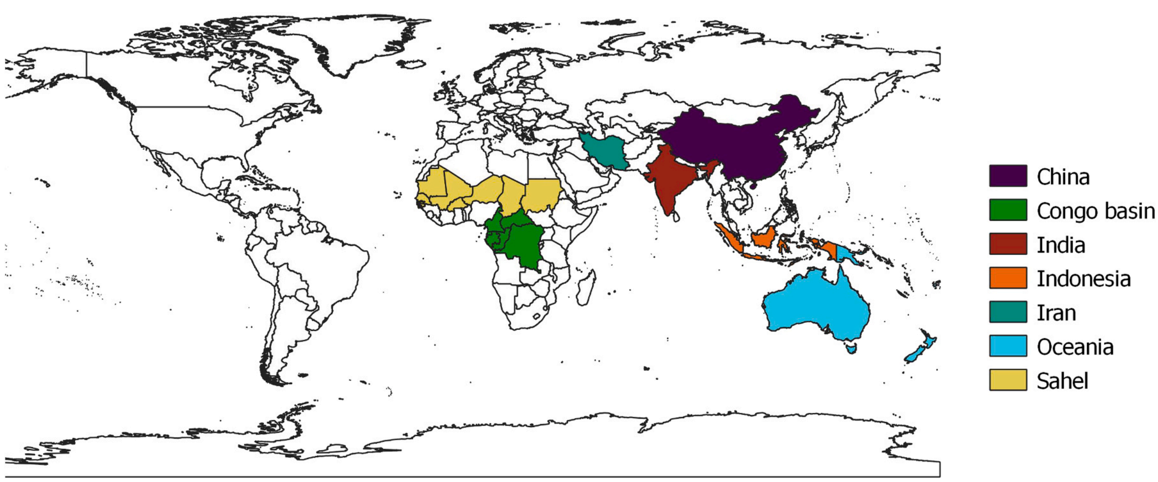

Fig. 1. Locations of the regions or case studies analyzed in this study.

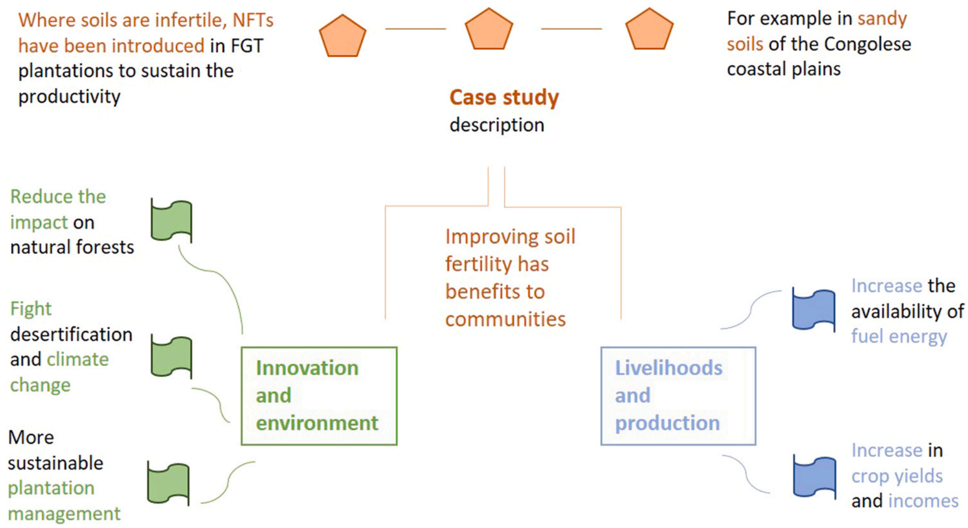

Fig. 2. Benefits of introducing Nitrogen-fixing species (NFS) in forest plantations with Fast growing Tress (FGT) in the Congolese coastal plains meeting the objectives of the "4p1000" Initiative.

although responsible for emitting only 25 Mt of CO_2e per year, equivalent to the emissions of the Paris metro area, is very susceptible to negative effects of climate change, including drought (Assouma et al., 2019; Rahimi et al., 2021; Tagesson et al., 2016).

Climate change severely affects Sahel's forest ecosystems, worsening drought, desertification, and biodiversity loss, and undermining local livelihoods (Epule et al., 2017; Giannini, 2010). Frequent, severe droughts lead to water scarcity, soil moisture loss, and forest decline, with many tree species unable to survive extended dry periods (Giannini et al., 2013; Hein et al., 2009). Altered rainfall patterns disrupt tree regeneration and growth, while rising temperatures stress ecosystems, diminishing water availability and suitability for some species (Biasutti, 2019; Diallo et al., 2020). These changes threaten the C sequestration role of forests, potentially exacerbating climate change impacts (Assouma et al., 2019; Sinare et al., 2022).

2.1.2.2. Practices with potential to foster SOC sequestration. Conservation agriculture (CA) practices and agroforestry are systems recognized as having potential to sequester C in the region (Sun et al., 2020; Plieninger, 2011; Beillouin et al., 2023). The potential of CA in dryland ecosystems, such as Kenya, was demonstrated by Rabach et al. (2020). Valkama et al. (2020) used a process-based crop model to simulate the contribution of different CA components to SOC sequestration and concluded that all three CA principles (minimum soil disturbance, permanent soil cover, and crop diversity) are likely to be increasingly relevant for SOC sequestration under changing climate conditions. In a recent review focused on sub-Saharan Africa, Corbeels et al., (2019) found that CA could only significantly increase SOC stocks if the three principles of CA were combined together. No-tillage alone has no impact on SOC stocks, and crop residue retention is the most important principle to drive SOC increase, as also found in a recent study on long-term CA in Zimbabwe (Shumba et al., 2024).

Reviews of the impact of different agricultural systems on SOC sequestration (Bruce et al., 1999; Friedlingstein et al., 2022; Ingram and Fernandes, 2001; Lorenz and Lal, 2018; Nair et al., 2021; Schleicher et al., 2017; Powlson et al., 2016; Beillouin et al., 2023) showed C sequestration rates for CA vary with climatic zone and crop type across Africa.

There is some evidence that the effectiveness of CA to store additional SOC varies with regional climates, and that farms in arid regions may benefit more from CA than those in humid regions, with a win-win outcome in terms enhanced C sequestration and increased crop yield (Sun et al., 2020), indicating the need for regionally adapted CA practices. However, regions where it would be more beneficial for farmers are not necessarily the ones with the highest climate change mitigation potential. Gonzalez-Sanchez et al., (2019) found higher C sequestration rates in tropical and equatorial zones of Africa compared to the Mediterranean and Sahel zones, suggesting that CA practices have greater potential to contribute to climate change mitigation in regions with more favorable climatic conditions. These authors also estimated a potential annual C sequestration in African agricultural soils through CA of 143 Tg of C yr^{-1}. However, in a rebuttal, Corbeels et al. (2020a) showed that this estimation was largely overestimated, and that the maximum potential would be less than 11 Tg C yr^{-1}. CA combining the three principles can increase crop yields in SSA, but only slightly and in the long-term (Corbeels et al., 2020b). Promoting and implementing CA practices in region can therefore play a role for soil fertility improvement, food security and contribute to climate change mitigation with the objectives of the "4 per 1000" Initiative.

2.1.2.3. Factors affecting the potential for sequestration. However, adoption of CA throughout SSA, including the Sahel, is currently very low (Andersson and D'Souza, 2014) for many reasons. A major constraint is the lack of immediate increase in farm income with CA (Corbeels et al., 2014). Two other major reasons are related for instance to labor constraints (Rusinamhodzi 2015a) or to competition for biomass with livestock (Baudron et al., 2015; Rusinamhodzi et al., 2015b). CA promotion without support to tackle these numerous socio-economic constraints faced by farmers is unlikely to lead to widespread adoption. Depending on the specific context, many other practices could be more relevant for farmers in SSA, with associated co-benefits for SOC. There is no one-size-fits-all solution and a basket of options should be considered, including agroforestry, intercropping, temporary grasslands and improved crop-livestock integration, integrated soil fertility management, and biochar.

2.2. Asia

Asia is a vast continent with a heterogeneous population, economy, environment, and social and political settings. The continent has witnessed a massive economic portfolio shift in recent decades. Although agriculture is still essential unprecedented land use change/cover change has altered its environment, including soils (e.g., Chen et al., 2022). Growing population, developmental activities, and the need for food and water resources have increased land degradation across this continent (ADB et al., 2021; Naderi Beni et al., 2021).

Unprecedented land degradation has ruined pristine soil formations and structures, leaving little or no organic matter in most arable lands in these countries. Unsustainable cultivation, developmental activities, erosion, compaction and soil pollution by toxic materials such as arsenic, cadmium, cobalt, chromium, copper or nicker (Hou et al., 2025), have contributed to the degradation of topsoil. The annual average decline of the total terrestrial land CO_2 sink in Asia was estimated at about −1.56 Pg C yr^{-1} from 2006 to 2010 (Zhang et al., 2014). Large scale studies (several countries scale) (Lal, 2002) as well as studies at country level (Liu et al., 2020) propose that there is a potential for SOC sequestration. Nevertheless, their informative value is somehow limited, as they do not account for regional variations and uncertain dynamics of SOC sequestration (Cheng, 2020). Overall, studies have emphasized new sustainable practices such as regenerative agriculture in Southeast Asian croplands (Tan and Kuebbing, 2023, Leng et al., 2024), as long-term solutions for the region to reclaim SOC content.

2.2.1. Southeast Asian humid tropics: Indonesia case study

2.2.1.1. Land-use and regional context for SOC sequestration. The climate in Southeast Asia includes humid tropics, equatorial climate and tropical rainforest zones (Koppen classification) and is characterized by a high rainfall with average annual precipitation of 1500–2500 mm (Van Noordwijk et al., 1997). Intensive temperature and rainfall often result in highly weathered and leached soils with accumulation of iron and aluminium oxides (Stahr and Herrmann, 2023), but in regions such as parts of Indonesia with volcanic activity, soils like those in islands of Java and Sumatra are continually renewed by fresh volcanic materials. Volcanic ash derived soils are generally high in SOC with topsoil levels of 3–5 % (Fiantis et al., 2022).

Indonesia's land use and farming systems are diverse, due to its vast geographical spread across thousands of islands, varied climates, and ecological zones. Broadly the farming system is divided in lowland, mostly paddy rice and seasonal crops, upland for perennial crops, and coastal areas. Smallholder Farming is the most common farming system, characterized by mixed cropping practices. The largest contribution to GHG emissions in the agriculture sector is deforestation. From 2001–2023, Indonesia lost about 292,000 ha of primary forest, resulting in about 221 million tonnes of CO_2 emissions (Global Forest Watch https://www.globalforestwatch.org/, Accessed 1 April 2025).

Recognizing agriculture as a significant contributor to GHG emissions in Indonesia, the government has launched initiatives such as *Low Carbon* and *Climate Smart Agriculture* (Savelli et al., 2021). These programs focus on employing site-specific technologies for sustainable farming practices, reducing emissions caused by rice residue burning and improving manure management. However, the issue of deforestation is still lingering.

2.2.1.2. Practices with potential to foster SOC sequestration. Management practices aimed at enhancing agricultural SOC content in Indonesia have been tailored to different agricultural systems and landscapes to leverage the unique environmental characteristics and support sustainable agricultural production. In the lowland farming systems, focusing on paddy rice and seasonal crops, practices include implementing conservation tillage methods to help maintain soil structure and organic matter, thus minimizing C loss due to erosion and decomposition. Burning crop residues remains common, and reducing this practice would benefit soil health and air quality (Sofiyuddin et al., 2021).

In soils derived from recent volcanic ash deposition, cultivated soils can have a higher SOC stock, exchangeable bases, pH and phosphorus levels than forest soils, which is likely due to regular amendments and the stabilization of SOC by non-crystalline minerals (Anindita et al., 2023). Effective management of paddy rice cultivation has increased SOC levels (Minasny et al., 2011). Retaining rice straw in the soil can boost SOC levels, but can also lead to increased methane (CH_4) emissions. Mixing straws into the soil or applying biochar could mitigate CH_4 emissions (Lee et al., 2020). It has been estimated that adopting water management techniques in rice paddies, e.g., controlled flooding and intermittent drainage, could decrease GHG emissions from Indonesian paddy soils by an average of 37 % (Hadi et al., 2010). In addition, reducing tillage and deep fertilizer placement could also reduce CH_4 emissions (Wihardjaka et al., 2023).

In upland farming systems, particularly those dedicated to perennial crops, SOC storage may be enhanced using strategic management practices such as agroforestry (Achmad et al., 2022). Tree species with deep root systems contribute to SOC accumulation through root biomass and leaf litter deposition, providing shade and wind protection for understory crops and reducing soil erosion (Hairiah et al., 2020). Perennial crops such as oil palm, coffee, and rubber could contribute to SOC stocks over the long term, when managed well (Rahman et al., 2021). For example, in the oil palm system, soils in the inter-row zone with diverse understory plants could store significantly more SOC and support biodiversity (Ashton-Butt et al., 2018; Rahman et al., 2021). Agroforestry systems, such as alley cropping or silvopasture, integrating trees or shrubs alongside cash crops or livestock, and incorporating leguminous tree species can enhance soil fertility. As well as enhanced C sequestration through increased vegetation biomass, these systems promote soil health and biodiversity, reduce land degradation, and support food security (Duguma et al., 2023). Converting degraded lands to agroforestry in tropical countries has been highlighted as an option for achieving Nationally Determined Contribution (NDC) commitments (Duguma et al., 2023). Implementing smallholder agroforestry systems can not only store as much C per hectare as some secondary forests but increase resilience to dry seasons as demonstrated in shifting from cocoa monoculture to agroforestry (Gusli et al., 2020), and enhancing smallholder livelihoods (Roshetko et al., 2002). While limited in scale, organic farming practices can also increase SOC where incorporating crop rotations and green manures helps maintain soil fertility and structure while continuously adding C inputs (Komatsuzaki and Syuaib, 2010).

2.2.1.3. Factors affecting the potential for sequestration. The adoption of practices that decrease GHG emissions such as reduced tillage agriculture, water management for paddies, residue retention, and regenerative practices is still very low due to traditional beliefs and reliance on manual labor. Nevertheless, no-tillage systems have been trialed at the local scale in Java and the results indicated no-till had the benefit of reducing labor cost, which may be attractive to smallholder farmers (Lisanty et al., 2023).

A critical issue for Indonesia is reducing emissions caused by land use change. Indonesia has one of the largest peatland areas and coastal wetlands in the tropics, each representing very large C stores. Strong policy and enforcement are needed to protect peat swamp forest from further deforestation and drainage, and the environmental problems these activities cause, including high C losses to the atmosphere. The blue C pool, including mangrove ecosystems store a large amount C (organic and inorganic) in sediments, trees, seagrasses, and soils. Indonesia's seagrasses and mangroves were estimated to store about 3.4 Pg C, which constitutes 17 % of the world's blue C reservoir (Alongi et al., 2016).

2.2.2. South Asia

2.2.2.1. Land Use Changes and Regional Context. South Asia is a global hotspot for climate change, grappling with tremendous pressure on land and water resources to sustain its rapidly growing population. The agricultural sector, predominantly cereal-based and covering about 40 million hectares, is particularly vulnerable. Small-scale and marginal farmers dominate the landscape and typically rely on intensive farming practices, which contribute to the loss of soil organic carbon (SOC) (Jat et al., 2022).

Cereal cropping systems often include mixed or monoculture cereals followed by non-cereal crops such as legumes, vegetables, or potatoes in annual rotations (FAO, www.fao.org). As the region prepares for a projected 40 % increase in food demand by 2050 (Bodirsky et al., 2015), it faces substantial challenges, especially since 94 % of arable land is already in use. Moreover, 58 % of agricultural areas are under stress from factors such as water scarcity and extreme heat (Amarnath et al., 2017), trends expected to intensify under future climate scenarios (Muthukumara et al., 2018).

Rapid economic development has further escalated greenhouse gas (GHG) emissions. In 2017, South Asia contributed 7.5 % of global CO_2 emissions from fossil fuel combustion, with India alone accounting for 6.6 %. Agricultural emissions, largely from CH_4 and N_2O, represented 17 % of global emissions in 2017—a 179 % rise since 1990. India was responsible for 11.8 % of these emissions, with the remaining 5.2 % from other South Asian countries.

2.2.2.2. Practices with Potential to Foster Soil Organic C Sequestration. Conventional farming practices in South Asia—marked by heavy tillage, intensive cropping, and indiscriminate agrochemical use—have contributed to the degradation of soil organic matter (SOM) and SOC. The Green Revolution, although successful in boosting food production, encouraged these practices, leading to long-term soil health concerns. One particularly detrimental practice has been the large-scale burning of crop residues: around 2 million farmers in northwest India burn approximately 23 million tons of rice residues annually (Lohan et al., 2018).

Such practices not only lead to C loss but also contribute to severe air pollution and public health issues. For example, in 2017, particulate air pollution levels in several northwest Indian cities exceeded safe thresholds by more than five times (Cusworth et al., 2018).

Mitigating these challenges will require the adoption of SOC-enhancing practices such as conservation agriculture, reduced tillage, residue retention, diversified crop rotations (especially with legumes), and precision nutrient management.

2.2.2.3. Factors Affecting the Potential to Recast Soil Organic C Sequestration. The potential to increase SOC stocks is shaped by several biophysical and socio-economic constraints in South Asia. First, the overwhelming dominance of smallholder farmers and fragmented landholdings limits the scalability of SOC-friendly practices. Second, the widespread practice of crop residue burning, driven by labor shortages and the absence of cost-effective alternatives, significantly hampers SOC conservation efforts.

Additionally, the region's high vulnerability to climatic extremes (heat, droughts, and flooding) and the already intensive land use system restrict opportunities to implement long-term soil-restoring measures. SOC sequestration also competes with other pressing objectives—namely food security, water conservation, and air quality improvements.

Finally, policy incentives, awareness, and access to knowledge and resources are critical determinants. Without substantial investment in farmer education, infrastructure (e.g., residue management technologies), and enabling policy frameworks, the potential for meaningful SOC sequestration will remain under-realized.

2.2.3. West Asia drylands

2.2.3.1. Land-use and regional context for SOC sequestration. The West Asia region covers large areas of drylands. Like other drylands (e.g., Plaza-Bonilla et al., 2015), West Asian drylands have been subject to vegetation loss, soil erosion and desertification, leaving many areas exceeding their safe carrying capacity. Over the past 50 years, extensive land use change due to urbanization and industrialization have left most of these areas degraded, causing them to get exposed to severe consequences. Additionally, extensive conventional agriculture has consumed most of surface and underground water resources while increasing land subsidence.

Even though drylands may generally have a lower SOC content, a study shows that global dryland soils can store 646 Pg of organic C to a depth of 2 m (32 % of the global organic C pool) (Plaza et al., 2018). The storage capacity differs between ecosystem types and from one country to another (e.g., Lal, 2002). For instance, in drylands, forest ecosystems can contain higher C stocks than barren lands.

2.2.3.2. Practices with potential to foster SOC sequestration. A community-based project called, in short, the "Carbon sequestration project" was initiated by the Iranian government with partial funding from the UNDP/GEF in 2003 (Amiraslani, 2021). It showed that the implementation of some conservation practices (e.g. seeding, afforestation) with the help of empowered local communities could enhance soil health and C sequestration capacity. Simultaneously, such locally supported soil improvement initiatives reduce poverty by creating jobs and a sustainable environment.

2.2.3.3. Factors affecting the potential for SOC sequestration. West Asia predominantly comprises vast natural deserts and barren lands which are potentially low-priority areas for C sequestration. Droughts and floods are natural features of hydrologic patterns but there are growing concerns that climate change will further hamper soil improvement actions in the future. In drier countries, droughts exacerbate the challenges for improving SOC and SOM content and stabilization.

Soil and land degradation and climatic conditions have increased food insecurity risks in the region and many of these countries, notably rich oil-exporting states, rely on food imports. Large-scale efforts have been made to reclaim some parts of the degraded lands in Iran (Amiraslani and Dragovich, 2010; 2011), providing a way for the improvement of SOC content and SOM, contributing to the objectives of the "4 per 1000" Initiative and the UN Agenda 2030 for Sustainable Development.

2.2.4. East Asia: China case study

2.2.4.1. Land-use and regional context for SOC sequestration. China, as the largest food producer and leading food exporter in Asia, is also one of the top GHG-emitting countries globally. Climate change poses threats to food security, prompting China to establish goals for mitigation. SOC sequestration has emerged as a crucial component of China's mitigation strategy, particularly within its NDC and broader development plans (Lu et al., 2022).

A particular issue in China is the management of black soil (Mollisols or Chernozems), which covers approximately 6 million ha in Northeast China, referred to as the "giant panda" of China's arable land due to its rich organic C content (Yu et al., 2006). These loamy soils developed on loess-like parent material, are highly fertile but vulnerable to severe wind and water erosion due to intensive cultivation. Conservation tillage technologies and soil protection measures are being implemented to prevent further degradation.

2.2.4.2. Practices with potential to foster SOC sequestration. Recent policy initiatives underscore China's commitment to enhancing SOC sequestration. The 14th Five-Year Plan (2021–2025), focuses on improving ecosystem C sequestration capacity, monitoring emissions reduction, and fostering technological innovation in the agriculture sector. Soil conservation and agricultural sustainability initiatives, such as agricultural straw recycling, expansion of organic fertilizer use, and protection of black soil (Mollisol), aim to improve C sequestration in agricultural systems. Research and management efforts emphasize protecting fertile agricultural soils, increasing SOC sequestration, enhancing nutrient use efficiency, remediating contaminated and degraded soils, monitoring soil health, and quantifying soil changes in space and time (Zhang et al., 2022).

Studies over the past few decades have highlighted the importance of increasing SOC in cropping soils through enhanced plant production and residue return. Between 1980 and 2011, intensive farm management practices, such as fertilization and crop straw return, increased topsoil SOC stocks (0–20 cm) by 4.3 Mg C ha^{-1} in China's croplands (Zhao et al., 2018). Lu et al. (2018) estimated that SOC stocks in China's forest, shrubland, and grassland ecosystems increased by 1.0–9.7 Mg C ha^{-1}, primarily due to ecological restoration projects initiated since the late 1970s.

2.2.4.3. Factors affecting the potential for SOC sequestration. While SOC sequestration efforts offer promising climate benefits, trade-offs are possible for some practices such as increased fertilization. Sun et al. (2023) demonstrated that in eastern China, the increase in SOC on cropland over the past 20 years was accompanied by soil acidification of approximately 0.7 pH units (Zhang et al., 2020). In addition, acidification caused a significant loss of soil inorganic C (Song et al., 2022).

Several estimates highlight the sequestration potential of China's terrestrial ecosystems. Croplands, covering over 130 million ha, could sequester up to 10 billion tons of CO_2e, equivalent to offsetting two years of China's total emissions (Qin et al., 2013). In another estimate the SOC sequestration rate ranges from 60 to 100 million tons of CO_2e per year, approximately 10 % of annual agricultural emissions (Sun et al., 2010), while (Huang et al., 2022) suggested that by increasing forests and wetlands, China's terrestrial ecosystems could sequester 1.5 billion tons of CO_2e, offsetting 12–15 % of energy-related peak CO_2e emissions by 2060.

While forests account for the majority of this sequestration potential, croplands also hold significant potential for SOC sequestration and addressing soil degradation. However, challenges remain in scaling up sequestration efforts and accounting for trade-offs (Cheng and Pan, 2016). As SOC sequestration is gaining prominence in China's journey towards net-zero emissions, concerted efforts across policy, technology, and scientific research offer a pathway towards more sustainable agricultural practices and environmental stewardship. However, the success of these initiatives, particularly in cropping systems like rice production, will largely depend on farmers' awareness, environmental attitudes, access to technical support, and availability of financial incentives (Li et al., 2020; Chen and Chen, 2022).

2.3. Oceania

2.3.1. Land use and regional context for SOC sequestration

Oceania is a region with a land surface area of 8.526 M km^2 extending over 100 M km^2 of the Pacific Ocean, and an estimated population in 2023 of around 45.5 million (Worldometer, 2024). Of the total land area, Australia occupies almost 93 % (7.692 M km^2), Papua New Guinea (0.463 M km^2) and New Zealand (NZ) (0.286 M km^2) with the remainder across the many smaller islands of Melanesia, Micronesia and Polynesia. All parts of the Oceania region experience a strong maritime influence, and all people share a strong dependence on the health of their soil and ecosystems for domestic food requirements, income from food and fiber production, and from nature tourism. However, there is within Oceania, enormous biophysical, social, cultural and economic diversity, which affects land use and land management and determines the types of interventions that are effective and can be implemented to foster soil carbon storage.

Anthropogenic climate change is already seen in accelerating trends of extreme weather events and sea level rise that threatens settlements, food production and natural ecosystems, especially in low-lying Pacific Least Developed Countries and Small Island Developing States[4] (IPCC et al., 2023). Agriculture and land management are at the forefront of responses to these impacts (Brown et al., 2023), but the challenging climate, and biophysical characteristics, sometimes in combination with low economic status limit the management options available to farmers and other land managers. Even in more developed countries of the region, such as Australia, the evidence-base for location-specific management strategies that are effective in fostering SOC sequestration is limited for some areas (McDonald et al., 2023; Henry et al., 2024). Case studies from three contrasting areas of Oceania illustrate how regional land use and biophysical constraints define management practices with the greatest potential to foster SOC sequestration.

2.3.2. Practices with potential to foster SOC sequestration

Case study 1: The Loyalty Islands

The Loyalty Islands Province in New Caledonia is a series of uplifted coral atolls sitting on volcanic bedrock. Fire-fallow or slash-and-burn agriculture has traditionally been the main food production system used by the Kanak people on Gibbsic Ferralsols (Humic) soils. Under this system, the native vegetation is slashed and burned before crops are planted and, following harvest, a long period of 'fallow' allows natural vegetation to recover. Policies introduced over the past two to three decades have encouraged local communities to switch from traditional farming to planting perennial orchards to generate new income.

Samples taken on the main island, Maré Island (21° 31′ 00″ S; 167° 59′ 00″ E), showed that under traditional management SOC content was high (71.9–194.4 Mg C ha^{-1} in an equivalent soil mass of 2000 Mg ha^{-1}) and not significantly different from adjacent native forest soils (Leopold et al., 2021). However, samples collected from sites converted in 2010 from traditional practices to avocado orchards showed that stocks declined over several years by about 30 % compared to forest soils even when the orchards were established on fields in secondary forests that had already experienced some SOC loss (Leopold et al., 2021). The data indicate that traditional systems maintain SOC and fertility due to organic matter inputs during the long fallow period and nutrient release during burning of vegetation after slashing before re-planting (Hauser and Norgrove, 2013). In contrast, implementation of the perennial horticulture system, which commonly involves only an initial fertilizer application at the time of orchard establishment, was found to be insufficient to prevent loss of SOC and may not be sustainable.

Case study 2: The Australian rangelands

Approximately 75 % of the total land mass of Australia (7.692 M km^2) is classified as rangelands (ACRIS, 2008), predominantly managed for extensive ruminant livestock production (Bastin et al., 2009). The rangelands are characterized by low and variable rainfall and soils that are highly weathered and naturally low in organic matter, most soils having 30–40 Mg C ha^{-1} and some as little as 10 Mg C ha^{-1} (Viscarra Rossel et al., 2014). Significant areas have also been degraded by past agricultural practices with substantial loss of SOC (Sanderman et al., 2017). Low net primary production (NPP) (Liu et al., 2017), vast areas, and high soil and landscape diversity are significant constraints on implementing and monitoring new practices to increase or maintain SOC stocks. To foster the adoption of practices to sequester SOC in agricultural soils, the Australian government introduced a C crediting method in 2014 as part of a legislated C farming scheme (Henry et al., 2023), and since then interest and research investment have increased to better understand which practices are effective for C sequestration.

In Australia's rangelands, climate and soil factors typically determine up to 90 % of the variation in SOC levels (Rabbi et al., 2015). The effect of management is small, but from long-term field trials there is evidence linking practices with regional benefits for C sequestration: (i) Avoiding prolonged high stocking rates; (ii) Sowing more productive

[4] http://hdr.undp.org/en/content/latest-human-development-index-ranking

grasses or introducing legumes into grass pastures; (iii) Converting from cultivated cropping to permanent pasture (Henry et al., 2024). However, the evidence is less clear for some practices that have been promoted as favorable for C sequestration, such as destocking which showed a non-significant effect except where sites were initially degraded and restoration of depleted SOC was possible, and rotational grazing practices where research data for SOC were found to be inconsistent (McDonald et al., 2023; Henry et al., 2024). The vast areas of rangelands mean that even modest C sequestration per ha, e.g. rates of 0.1 Mg ha^{-1} yr^{-1} up to 0.3 Mg ha^{-1} yr^{-1} for planting legumes or 0.4 Mg ha^{-1} yr^{-1} for conversion from cropping to permanent pasture (Henry et al., 2024) have the potential to contribute significant climate change mitigation.

Case study 3: New Zealand's C-rich agricultural soils

New Zealand (NZ) soils are relatively high in SOM and average almost 100 Mg C ha^{-1} in the top 30 cm (Hewitt et al., 2021; Mudge et al., 2021). Cultivation was first carried out by Māori about 750 years ago, but more intensive agricultural development did not begin until around 1840. Approximately two-thirds of NZ land is now used for food production, plantation forestry or other human use (Forbes et al., 2020).

The naturally high SOC content means that opportunities for further C increase are likely to be limited, except in those areas where changes in land use (e.g., from forest to agriculture) have depleted SOC stocks (McNeill et al., 2014; Mudge and Schipper, 2021). Perennial pastures typically have the highest SOC stocks, annual cropland the lowest, and forests have intermediate values. Current high levels mean that maintaining existing C stocks at optimal levels is likely to be the best strategy for climate change and sustainability objectives as well as agricultural productivity and income, but the influence of different practices is not well understood within each land use category to inform management decisions (Whitehead et al., 2018). Research on which strategies can realize the benefits of maintaining C-rich soils of NZ and where it may be feasible to increase storage to contribute to objectives for climate change mitigation as articulated in the "4 per 1000" Initiative. Strategic monitoring of SOC across NZ has been initiated to quantify current stocks and identify where earlier losses have occurred (Hewitt et al., 2021; Campbell et al., 2021).

The three contrasting regions and land management systems of Oceania described in the case studies above highlight the need for regionally specific trials to determine effective practices and to identify locations where management strategies have reliable potential to increase SOC stocks or to maintain existing SOC stocks in naturally C-rich soils (Mudge and Schipper, 2021).

2.3.3. *Factors affecting the potential for sequestration*

Due to the lived experience of climate impacts across many parts of Oceania, recognition of the importance of the land sector in climate change mitigation is high relative to less-affected regions of the world. Many land managers are interested in implementing practices in agricultural, forestry and natural landscapes that contribute to climate change mitigation, climate resilience and food security. The diversity in biophysical potential and land use is matched by a high degree of variation in socio-economic status of different communities and jurisdictions, highlighting the need for better understanding of actions that are effective and practical for farmers and foresters interested in maintaining and enhancing SOM and SOC. Even in more developed countries of the region, such as Australia, the evidence-base for location-specific management strategies that are effective in fostering SOC sequestration is limited for some areas (McDonald et al., 2023; Henry et al., 2024). The specific socio-economic situation will influence the implementation of management strategies identified as having benefits for climate change and/or for sustainable production. For example, Case Study 1 from the Loyalty Islands demonstrates how better understanding of the location-specific soil carbon balance in farm systems and learning from traditional knowledge and practices and social organization sustained productivity to avoid negative outcomes for economic status, food security and SOC storage (Leopold et al., 2021). Including socio-economic considerations as well as biophysical opportunities and constraints is critical to the adoption of regionally appropriate management to provide climate change and food production benefits aligned to the objectives of the "4 per 1000" Initiative.

3. Discussion and conclusions

The capacity for SOC sequestration, along with the selection of appropriate management practices to promote soil health and C sequestration, are greatly influenced by regional ecological and socio-economic factors. This paper provides insights into the diverse approaches observed across various global regions, each of which has proven effective within its own context in furthering the objectives of the "4 per 1000" Initiative.

In the countries of the Congo Basin, with the world's second largest rainforest and the largest tropical peatlands, the success of implementing "4 per 1000" objectives relies on appropriate practices such as agroforestry, forestry (planted and managed natural forests) and agricultural practices involving trees. This will help in (i) fostering healthy soils rich in C and better crop yields, (ii) preserve natural and boost planted forest (enhancing ecosystem services they provide). Preference must be given to local species and the involvement of local and rural communities need to be reinforced and encouraged; (iii) mitigate climate change through C sequestration in soil and biomass; provide pulp and fuel wood energy for industry and local population, (iv) enhance land restoration and biodiversity for sustainable development.

Climate change already severely affects *Sahel ecosystems*. Conservation agriculture (CA) is considered to have potential to slightly increase C sequestration throughout Africa in the long term, with biggest effects expected when all three principles are applied. Yet, adoption rates are still very low and socio-economic constraints, like labor and biomass availability need to be tackled to allow widespread adoption. Depending on the specific context, many other practices (like agroforestry, intercropping, temporary grasslands and improved crop-livestock integration, integrated soil fertility management, biochar, etc.), could be more relevant for farmers in SSA, with associated co-benefits for SOC, and there is no one-size-fits-all solution.

The case study of *Indonesia* shows that the potential of organic farming practices is promising for C sequestration, though still limited in scale. In lowland paddy-rice systems adapted water management practices, the reduction of residue burning as well as applications of biochar help to reduce GHG emissions and increase C sequestration. In upland systems, combining agroforestry practices with plantation agriculture could represent a holistic approach to SOC management.

Drylands in West-Asia are facing severe soil degradation, which is expected to worsen due to impacts of climate change, negatively affecting SOC sequestration. Afforestation can help to improve the situation, as illustrated by the success of a program in Iran.

Over recent decades, in *China*, changes in management practices and restoration efforts have led to a significant increase in SOC, which can largely be attributed to increased plant productivity and residue return. This increase often comes at the cost of high fertilizer inputs with associated risks of trade-offs due to soil acidification. Recently, the reduction of GHG emissions from agriculture as well as C sequestration in the sector have been targeted explicitly in policies and a special emphasis is placed on conservation tillage in Chinese black soils.

The *Oceania and Pacific* region is highly diverse and climatic, edaphic, geophysical, socio-economic and cultural factors have a major influence on the objectives and practical solutions to increase and/or maintain SOC stocks in line with the objectives of the "4 per 1000" Initiative. Three examples illustrate how priority recommendations can be developed for local circumstances: (i) Where traditional fire-fallow farming are being modernised to perennial production systems managing the risk of loss of SOC should be based on monitoring programs combined with incorporation of local knowledge so that the transition processes do not lead to negative outcomes for food security, economic sustainability, and soil health; (ii) In vast areas of low-productivity rangelands managed for low-input grazing, the capacity for SOC sequestration is constrained by climate and soil factors as well as challenges for practical implementation. There is evidence that an improved understanding of practices such as sowing higher-producing grasses or legumes into native pastures and avoiding over-grazing can provide opportunities to increase or maintain SOC stocks while improving profitability and climate resilience; (iii) Where SOC stocks are naturally high, e.g. in the organic soils of New Zealand, the focus should be on establishing well-structured monitoring programs and research to understand how management can restore past SOC decline and avoid SOC loss following conversion for agriculture and forestry use.

CRediT authorship contribution statement

Jean-François Soussana: Writing – review & editing. **Claudia Schepp:** Writing – review & editing. **Beata Madari:** Writing – review & editing. **Beverley Henry:** Writing – review & editing, Writing – original draft, Conceptualization. **Alejandro Fuentes Espinoza:** Writing – review & editing. **Lydie-Stella Koutika:** Writing – review & editing, Writing – original draft, Conceptualization. **Claire Chenu:** Writing – review & editing. **Deborah Bossio:** Writing – review & editing. **Rémi Cardinael:** Writing – review & editing. **Jagdish Ladha:** Writing – review & editing, Writing – original draft. **Yuxin Ma:** Writing – original draft. **Budiman Minasny:** Writing – review & editing, Writing – original draft, Conceptualization. **Monika Skowronska:** Writing – review & editing. **Farshad Amiraslani:** Writing – review & editing, Writing – original draft, Conceptualization. **Consuelo Varela-Ortega:** Writing – review & editing. **Adesola Olaleye:** Writing – review & editing, Writing – original draft, Conceptualization.

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.

Acknowledgements

The authors thank all former STC's members for dedicating their time in promoting the objectives of the "4 per 1000 " Initiative from the very beginning i.e., Cornelia Rumpel, Yasuhito Shirato, Saidou Nourou Sall, Martin Kaonga, Eva Wollenberg, Magali Garcia Cadenas, David Whitehea, Brahim Soudi and Pete Smith.

Data availability

No data was used for the research described in the article.

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