Unlocking the Potential of Soil Organic Carbon: A Feasible Way Forward

Ronald Vargas-Rojas, Rosa Cuevas-Corona, Yusuf Yigini, Yuxin Tong, Zineb Bazza, and Liesl Wiese

1 Introduction

Soils have become one of the world's most vulnerable resources in the face of climate change, land degradation, biodiversity loss, and increased demand for food production (FAO and ITPS 2015). Notwithstanding the enormous scientific progress made in understanding the sustainable management of natural resources, the protection and monitoring of soil resources from national to global levels face complex challenges that restrict the design and implementation of on-the-ground policies. There is yet insufficient global support for meeting these challenges, which vary widely by region, and therefore for the protection and sustainable management of the world's soil resources (FAO 2017b).

Soil organic carbon (SOC) is a major component of soil organic matter (SOM) and plays a key role in many soil functions: it stabilizes soil structure and improves aggregation, which reduces soil erosion; improves absorption and retention of pesticides and other organic pollutants through their immobilization and degradation; enhances soil fertility by increasing nutrient cycling and storage; buffers crop production against water shortages by increasing soil porosity and aeration, water-holding capacity and hydraulic conductivity; and provides a habitat and food source for soil organisms by improving soil biodiversity and health (Lal 2004; Deb et al.

R. Vargas-Rojas (✉) · R. Cuevas-Corona · Y. Yigini · Y. Tong · Z. Bazza
Land and Water Division, Global Soil Partnership Secretariat, Food and Agriculture Organization of the United Nations, Rome, Italy
e-mail: ronald.vargas@fao.org

L. Wiese
Land and Water Division, Global Soil Partnership Secretariat, Food and Agriculture Organization of the United Nations, Rome, Italy

Department of Soil Science, Stellenbosch University, Western Cape, South Africa

H. Ginzky et al. (eds.), *International Yearbook of Soil Law and Policy 2018*,
International Yearbook of Soil Law and Policy,
https://doi.org/10.1007/978-3-030-00758-4_18

2015; FAO 2017a). The role of soils and SOC in the climate system and in the context of climate change adaptation and mitigation has only been recognized in recent decades, but it has been validated in various studies, both experimentally and through modelling (FAO 2017a). In fact, soils constitute the largest terrestrial carbon pool and play a crucial role in the global carbon balance by regulating dynamic biogeochemical processes and the exchange of greenhouse gases (GHGs) with the atmosphere. The preservation and/or increase of SOC stocks are therefore vital not only to improve general soil health but also to remove carbon dioxide (CO_2) from the atmosphere.

Because of its important role in soils, managing SOC as part of rehabilitating degraded soils is one of the key strategies for achieving land degradation neutrality (LDN). The conservation and monitoring of SOC stocks at different levels (national to global) is as complex as the nature and dynamics of SOC, requiring locally adapted policies to ensure the effective implementation of relevant practices. The study of soil organic carbon (SOC) represents a challenge because of its heterogeneous horizontal and vertical distribution. It may be present in thousands of organic compounds with different residence times (e.g., fast/active, slow/intermediate, and very slow/passive/inert), ranging from hours to millennia (Janzen et al. 1992; Schlesinger 1997; Gaudinski et al. 2000; Sohi et al. 2001; Lal 2002; Six et al. 2002; Field and Raupach 2004; Schmidt et al. 2011; Schlesinger and Bernhardt 2013; Gougoulias et al. 2014). The magnitude of SOC stocks is spatially and temporarily variable and is determined by different abiotic and biotic factors (Weissert et al. 2016). Our ability to detect vulnerable hot spots for SOC losses and gains and its uncertainty are still limited, and accurate baselines are still missing for many countries. On the other hand, the countries that do have the information present a high variability in reported values among authors, caused by the diversity of different data sources and methodologies. In order to enable comparability, every nation needs to quantify its SOC stocks in a harmonized way and implement management practices (designed and implemented for specific site conditions) aimed at preserving and (wherever possible) increasing[1] SOC stocks at a global level. In addition, it is essential to contribute to the generation of basic (i.e., measurements of SOC stocks) and specific information (i.e., measurements of carbon associated with fast-active, slow-intermediate, and very slow/passive/inert fractions) in order to gain an understanding of the mechanisms whereby SOC is sequestered and released into a global warming setting.

To elaborate the importance of maintaining and enhancing SOC in achieving LDN, reducing GHG emissions, and promoting climate change adaptation, the Global Symposium on Soil Organic Carbon (GSOC17) was held in March 2017 at the FAO[2] headquarters in Rome, Italy. The symposium's outcome document "Unlocking the Potential of Soil Organic Carbon" (FAO 2017b) defines a global

[1]The increase of SOC levels in soil require baseline data in order to plan actions and monitoring on the site in order to verify that the expected effects have been obtained.

[2]FAO—Food and Agriculture Organization of the United Nations.

agenda for action in support of SOC protection and management. The document aims to guide bold actions toward the maintenance and enhancement of SOC stocks for multiple land uses and users.

In this chapter, we underline the importance of SOC as related to climate change, human health, food security, and biodiversity. We also discuss the manner in which the GSP contributes to the study and knowledge of SOC by means of concrete activities and sound science. In particular, we focus on the implementation of activities in the GSOC17 outcome document, the input generated during the Global Symposium on Soil Organic Carbon that defines the way forward in connection with the measurement, mapping, monitoring, reporting, and preserving and/or increasing SOC stocks.

2 Why Is SOC Important?

The revised Soil World Charter (FAO 2015, p. 4) states:

> Soils are a key enabling resource, central to the creation of a host of goods and services integral to ecosystems and human well-being. The maintenance or enhancement of global soil resources is essential if humanity's overarching need for food, water, and energy security is to be met. In particular, the projected increases in food, fibre, and fuel production required to achieve food and energy security will place increased pressure on the soil.

This statement is in line with the need to restore degraded soils and improve soil health, which was identified as a way to achieve the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development. Specifically, sustainable SOC management would contribute to SDG 2 on ending hunger, SDG 3 on good human health and well-being, SDG 15 on life on land or biodiversity, and SDG 13, which tackles climate action (FAO 2017a).

Despite being the largest carbon pool, soil organic carbon stocks are vulnerable to losses when soil carbon is converted to greenhouse gases: CO_2 or methane (CH_4). Resulting declines in organic carbon stock negatively affect the soil's fertility and climate change regulation capacity. SOC stocks are especially sensitive and responsive to changes in land use, for example, from a natural state to an agricultural ecosystem or from forest to cropland.

The main causes of SOC losses differ widely between regions as a function of climate, types of soils, management practices and more. In sub-Saharan Africa, SOC loss commonly occurs because of the removal of natural vegetation, complete crop biomass removal from farmlands, and the high rate of organic matter decomposition by microbial communities, which is increased by higher temperatures. In Asia, SOC loss occurs mostly because of the use of crop residues as fuel or fodder, as opposed to returning them to the soil, and the degradation of grasslands. In Europe and Eurasia, drainage of peatlands has led to organic carbon loss, while in Latin America and the Caribbean, carbon losses are caused by deforestation, the ploughing of grasslands, and monoculture. In the Near East and North African region, a high turnover of SOC is mostly caused by high temperatures, along with changes in soil management practices. In North America, the main concern is the loss of SOC from northern and arctic soils due to climate change. Lastly, in the Southwest Pacific, the largest SOC losses have mostly been caused by the conversion of land for agricultural use (FAO and ITPS 2015).

2.1 Human Health and Food Security

SOC is key to maintaining soil fertility, which is crucial in supporting and sustaining plant growth by providing the nutrients needed for plant uptake and growth (FAO and ITPS 2015). Supplying nutrients for plant growth is facilitated by many processes that are directly related to SOC content. This includes nutrient storage in SOM, nutrient recycling from organic to plant-available mineral forms, and physical and chemical processes that control nutrient sorption, availability, and displacement, as well as nutrient losses to the atmosphere and water (FAO 2017a).

Both SOC and SOM have a significant effect on porosity, soil aggregation, and structural stability, which are important factors for soil aeration and water infiltration. A well-aggregated soil structure has an important role not only in decreased soil erosion and increased infiltration but also in the filtering of contaminants from the soil (FAO and ITPS 2015). SOC and SOM are therefore both important in regulating water quality and food production. It is also important to note that water stored in the soil contributes to 90% of the world's irrigation water for agricultural production and is the source of 65% of global fresh water (Amundson et al. 2015). This emphasizes the importance of SOC for human health and food security through direct contributions such as plant production and indirectly through the filtering of contaminants and the provision of fresh water for consumption and irrigation water.

3 Effects of Climate Change on SOC

Temperature and precipitation are the two most important factors in controlling SOC dynamics (Deb et al. 2015). Temperature is known to increase plant production and therefore to increase carbon inputs to the soil. However, increases in temperature (and in precipitation) can also increase the microbial decomposition of SOC, leading to decreases in SOC stocks worldwide (Keesstra et al. 2016). Figure 1 demonstrates the effect that an increase in temperatures has on SOC: a loss of soil carbon to the atmosphere, which would have a considerable impact on climate change (Crowther et al. 2016). This figure illustrates the carbon-climate feedback: increased temperatures fuel the loss of carbon to the atmosphere, which in turn leads to increased temperatures.

The Intergovernmental Panel on Climate Change (IPCC) has also projected an increase in extreme precipitation frequency, as well as an increase in droughts,

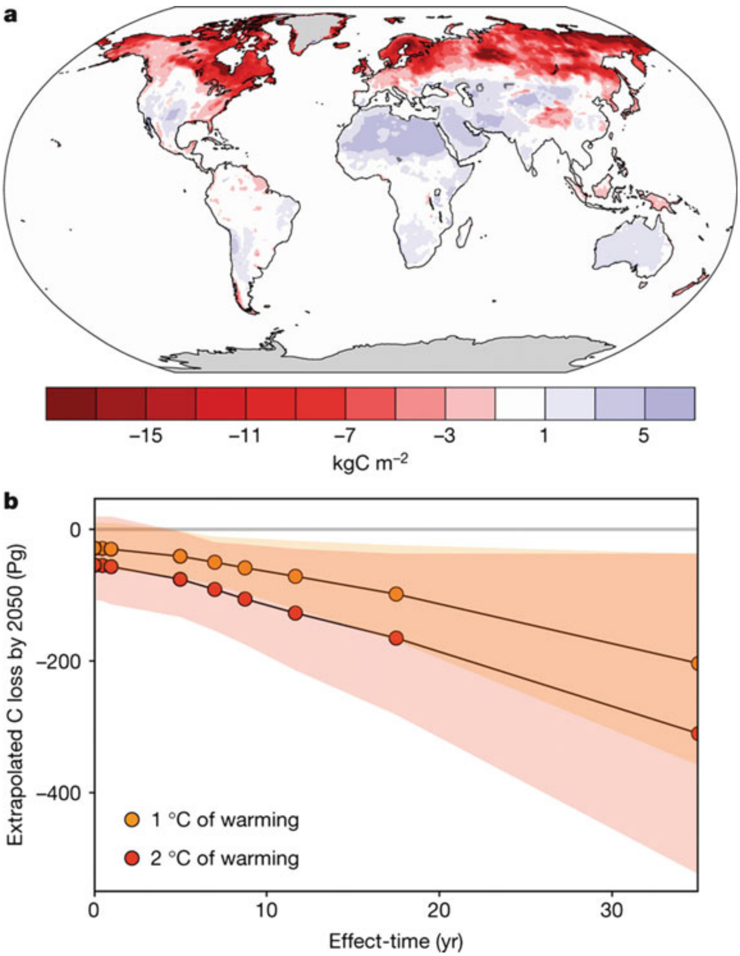

Fig. 1 Spatial extrapolation of the temperature vulnerability of SOC stocks (from Crowther et al. 2016). (**a**) Global map of the predicted changes in soil carbon stocks at a depth of 0–15 cm under a 1 °C rise in global average soil temperature (under the "no acclimatization" scenario). (**b**) Total decrease in the global carbon pool under 1 °C and 2 °C global average soil surface warming by 2050, as expected under a range of soil carbon effect-time scenarios on the *x*-axis. Effect time means the rate at which the full soil carbon response to increased temperature is realized. The shaded areas represent the 95% confidence interval around the average carbon losses for each scenario

leading to considerable effects on ecosystem dynamics (2014). An increase in the frequency of extreme events could have disastrous consequences, such as increased and accelerated soil erosion, increase in salinization, and all other degradation processes, which in turn would increase the loss of SOC, creating a vicious cycle (FAO 2017a).

There are many uncertainties when trying to make predictions and projections on the behavior of SOC as a function of climate change. The consequences of human actions on the global climate are still uncertain, mostly due to an incomplete understanding of soil respiration and its representation in Earth system models (Gougoulias et al. 2014). There is high uncertainty regarding the "priming effect" on SOM decomposition, which is one of the crucial processes in ecosystem carbon balances (FAO 2017a). The priming effect refers to an increase in decomposition of SOC stocks as a result of addition of compounds that are easily degradable (Van der Wal and De Boer 2017). This limits our predictions of future soil C responses to climate change as we still do not fully understand the mechanisms and consequences of the priming effect (FAO and ITPS 2015). Consequently, the uncertainty associated with any projections that would be made about the effects of climate change on SOC is increased.

Furthermore, the effect of microbial communities and changes in these microbial communities on climate change is still being researched and is not yet fully understood (Gougoulias et al. 2014). This adds further uncertainty to any projections as the behavioral response of these soil microbial communities to climate change is still unknown. This identifies a need to further study the GHG emissions from soils in order to better understand their contribution to climate change and the potential consequences that climate change can have on SOC. To achieve this, the priority has been set by FAO to have a good knowledge of the current global SOC stock and its spatial distribution. This information is crucial in informing various stakeholders that are directly involved with SOC to ensure that they are choosing the right management practices to mitigate and adapt to climate change (FAO 2017b).

4 SOC and Soil Biodiversity

Soil biodiversity refers to all the living organisms that are present in the soil. These organisms are constantly interacting, not only with one another but also with plants and animals (Orgiazzi et al. 2016). It includes organisms such as bacteria, fungi, protozoa, insects, worms, as well as other invertebrates and mammals. Soil biodiversity has an important role in food production and soil resilience to climate change (FAO 2017a). Similar to all the other processes mentioned, the dynamics of soil biodiversity is a complex process that can either contribute to the formation of SOM from organic litter or decrease its quality. This is due to the fact that the amount and quality of SOM contributes directly to the number and activity of soil biota (FAO 2017a). Soil biota is therefore influenced by the quality and quantity of SOC and only partially by plant diversity (Thiele-Brunh et al. 2012).

Figure 2 illustrates how unsustainable management practices in agriculture can lead to negative impacts on SOC stocks by affecting the complex web of interaction between pests and their natural enemies (Wall et al. 2015). This helps explain SOC losses that cannot solely be justified by physical soil properties as SOC is also dependent on the diversity of soil organisms and their activity (Gardi and Jeffery 2009). It is therefore very important to understand the relationship between SOC and soil biodiversity in order to determine how the loss of diversity that is currently

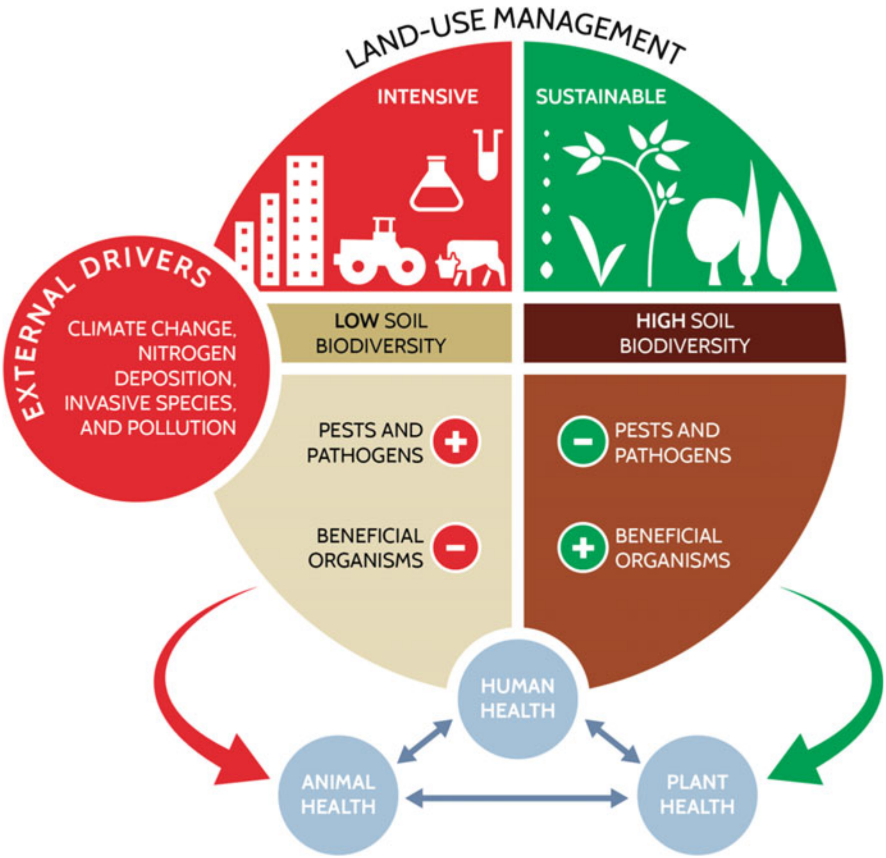

Fig. 2 The impacts of land use decisions on soil biodiversity, modified from Wall et al. (2015) (FAO 2017a)

happening will affect global carbon cycling processes (De Graaf et al. 2015). And finally, in addition to a better understanding of the mechanisms and effects of soil biodiversity on soils and SOC in particular, it is also important to adopt sustainable soil management practices to restore soil biodiversity and avoid any of the negative impacts associated with its loss.

5 Global SOC Stocks

The movement of C occurs in a cyclic manner through the pedosphere, atmosphere, hydrosphere, and biosphere at different spatial (from molecular to global) and time (ranging from days to hundreds of millions of years) scales. The biogeochemical C cycle involves two large annual transfers: the input of atmospheric CO_2 into plant

Table 1 Contribution of SOC to Four Global Requirements (Lorenz and Lal 2016; FAO 2018)

Requirement	SOC contribution
1. Maintaining soil functions and ecosystem services	Stabilizes soil structure and improves aggregation: reducing soil erosion Improves absorption and retention of pesticides and other organic pollutants: immobilization and degradation of organic pollutants
2. Sustaining long-term food security	Increases nutrient cycling and storage: improving soil fertility Improves soil water infiltration and retention: buffering crop production against water shortages
3. Climate change mitigation and adaptation	Stores atmospheric carbon dioxide
4. Maintaining soil biodiversity	Provides habitat and food source for soil organisms: improving soil biodiversity and soil health

biomass as a result of photosynthesis and the return of CO_2 into the atmosphere as a result of photorespiration by plants and respiration by microorganisms.

Globally speaking, SOC is higher (1500 Pg[3] C down to 1 m depth and 2500 Pg C at 2 m) than C in vegetation and C in atmosphere combined (about 650 Pg C and 750 Pg C, respectively) (Schlesinger and Bernhardt 2013; Batjes 2014). Total SOC stock is determined by the balance between the inputs of organic residues into soil and the loss due to erosion and decomposition processes. Plants are the main input source of C into soil through organic residues as vegetal debris and root exudates. Through SOM decomposition, all these residues are fragmented, transformed, and respired by soil fauna and microorganisms (SOM consists of roughly 58% C). The nutrient cycles and the energy that flows through ecosystems and agroecosystems largely depend on SOM decomposition rates.

SOC stocks can be significantly affected by human activities, especially those related to land use changes and agriculture, mostly as a result of SOM reduction, which leads to reduced soil quality and increased risk of soil degradation. At a global level, the leading cause of SOC loss is the transformation of natural ecosystems, which has led to a depletion of one billion tons of carbon that is being released into the atmosphere every year. Consequently, urgent action is needed to preserve and increase SOC stocks to reduce soil degradation, improve soil functions, and contribute to the global requirements defined in the GSP Pillar 1 Plan of Action to promote and implement sustainable soil management (SSM) (see Table 1). The first step toward preserving and increasing SOC stocks is to know where and how much these stocks currently are.

Jobbagy and Jackson (2000) pointed out that globally, the relative distribution of SOC with depth had a slightly stronger association with vegetation than with climate, but the opposite was true for the absolute amount of SOC. Total SOC content increased with precipitation and clay content and decreased with temperature. The researchers reported that the global SOC stock in the top 3 m of soil was

[3] 1 PgC = 1 billion metric tonnes of carbon.

2344 Pg C, or 56% more than the 1502 Pg estimated for the first meter. Global totals for the second and third meters were 491 and 351 Pg C, and the biomes with the most SOC at 1–3 m depth were tropical evergreen forests (158 Pg C) and tropical grasslands/savannas (146 Pg C).

The US Natural Resources Conservation Services (NRCS) reclassified the FAO-UNESCO Soil Map of the World at 2-minute resolution and combined it with a soil climate map. The resulting map shows the distribution of SOC to 1 m depth. Using this dataset, Kochy et al. (2015) calculated the soil organic carbon stocks as 1463 Pg. In addition, the authors reviewed current estimates of SOC stocks and mass (stock/area) in wetlands, permafrost, and tropical regions of the world in the upper 1 m of soil using the Harmonized World Soil Database (HWSD) v.1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). The HWSD provides one of the most recent global datasets of SOC, giving a total mass of 2476 Pg when using the original values for bulk density (BD). Adjusting the bulk density (BD) values in the HWSD for high organic carbon soils resulted in a calculated mass of 1230 Pg, while additionally setting the BD of Histosols to 0.1 g cm^{-3} (typical of peat soils) resulted in a total mass of 1062 Pg.

Scharlemann et al. (2014) reported that many estimates of global SOC stocks have been published during the past seven decades, most recently to support the calculation of potential CO_2 emissions from the soil under land use and land cover change (LULCC) and climate change scenarios. Although most studies report a global SOC estimate of roughly 1500 Pg C, there is considerable variation (median across all estimates: 1460.5 Pg C, range of 504–3000 Pg C, $n = 27$ studies).

5.1 Global Soil Organic Carbon Map (GSOCmap)

The most recent global estimate of global SOC stocks in the top 30 cm was conducted by FAO's GSP in 2017. The GSP and its Intergovernmental Technical Panel on Soils (ITPS) pursued a country-driven approach to compile a GSOCmap. The process was supported by an intensive capacity development and improvement program and a technical manual (Yigini et al. 2018) that provided countries with generic methodologies and the technical specifications to produce national SOC maps. The manual includes a step-by-step guidance to develop 1 km grids for SOC stocks, as well as the preparation of local soil data, the compilation and preprocessing of ancillary spatial data sets, mapping methodologies, and uncertainty assessments to strengthen member countries' capacities to produce national SOC maps. The GSP Capacity Development Programme not only increased the level of country engagement but also helped various countries to build national soil information systems.

The GSOCmap process was initiated after the United Nations Convention to Combat Desertification (UNCCD) Secretariat requested FAO and the GSP Secretariat to share information on potential pathways to improve global soil carbon knowledge and data. During the 5th Session of the ITPS held during March 2016, the GSP/ITPS were requested to conduct a global SOC assessment based on country-level spatial soil data sets, combined into a new global SOC map. As an action of the GSP and its members, this task would directly relate to SDG 15.3.1 and would also support the endorsed metrics for the assessment of LDN (FAO and GSP 2016).

Through its country-driven approach, the development of the GSOCmap provides and builds on synergies with ongoing and new reporting needs and data-sharing obligations. It therefore benefits activities at national, regional and global levels, particularly to

- enable training for countries in need of technical support (e.g., regarding the collection, statistical evaluation, and modeling of SOC data);
- develop data infrastructure to update the Status of the World's Soil Resources (SWSR) report on SOC through a country-driven baseline and initiate future assessments of SOC changes;
- support national GHG reporting: develop a valid, measurement-based inventory of reference SOC stocks for IPCC-Tier 2 assessments;
- further utilize SOC mapping activities to estimate the soil carbon sequestration potentials (e.g., through modeling) and the vulnerability of soil functions under climate change (with SOC as an indicator);
- contribute to the SDGs by developing national SDG-15.3.1 Tier 3 data for the subindicator on soil carbon;
- conduct harmonized assessments at different levels of action: GSP Regional Soil Partnerships, FAO regional and country offices, national soil information institutions, national statistics offices, and GEOSS[4] design principles for global data layers.

In early 2017, the GSP Secretariat contacted countries about their potential contributions to the GSOCmap project and informed them about the process and procedures. The data collection process is summarized in Fig. 3.

Countries with existing national SOC maps that met the specifications of this project shared their maps with the GSP Secretariat. Countries that did not yet have national SOC maps developed such maps based on the provided specifications. Where needed, the GSP Secretariat supported such national activities by organizing training sessions. If the in-country development of a SOC map was not possible because of insufficient capacity, the original SOC measurements were shared with the GSP Secretariat, which produced national maps in close cooperation with the national GSP focal points and/or institutional data providers. For countries that could not provide a SOC map or any original measurements, the GSP Secretariat used one of two gap-filling approaches: (1) spatial modeling using publicly available data or, (2) in the case of absence or insufficient amount of data, using publicly available SOC stock maps. This considerable effort culminated in the launch of the GSOCmap on World Soil Day (5 December) 2017, which was developed from more than one million profiles. Calculations using the GSOCmap (v1.2.0) (Fig. 4) suggest that soils

[4]GEOSS—Global Earth Observation System of Systems.

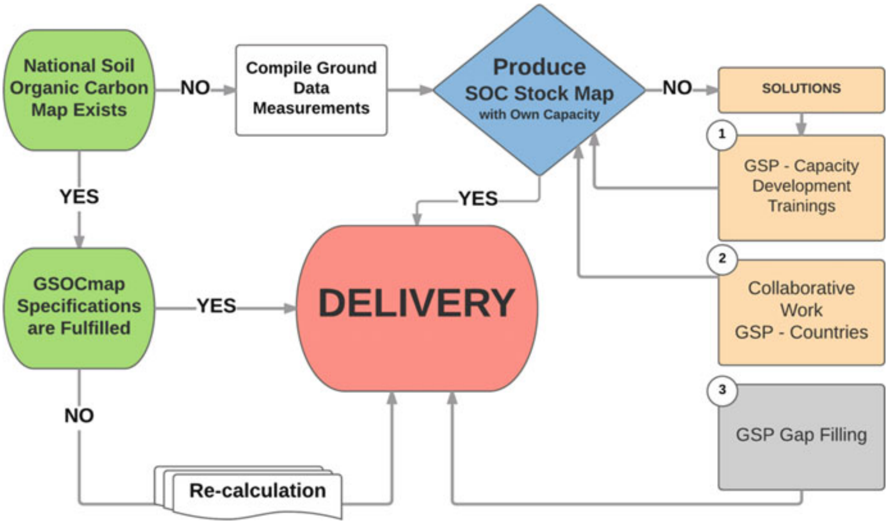

Fig. 3 Data collection process for the development of the GSOCmap

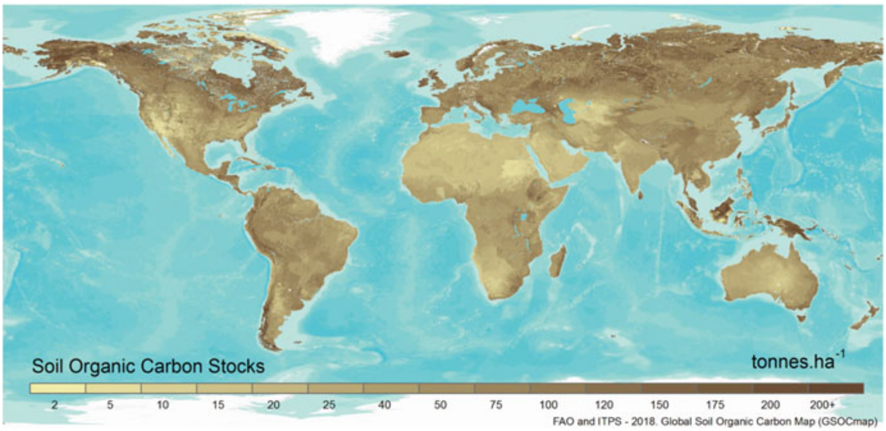

Fig. 4 GSOCmap V1.2.0 developed from more than one million profiles

hold about 680 Pg of SOC in the first 30 cm, which is similar to the value reported by Kochy et al. (2015) (Table 2).

Statistics for the countries were calculated based on the Global Administrative Units Layer as the source for country boundaries. Over 50% of the global SOC stocks at 30 cm are held by five countries: the Russian Federation (147.9 Pg—21.9%), Canada (80.2 Pg—11.9%), the United States of America (54.4 Pg—8.0%), China (45.2 Pg—6.7%), and Brazil (35.4 Pg—5.2%). Papua New Guinea and Indonesia have the highest mean SOC stocks (183.6 and 121.4 t/ha, respectively)

Table 2 Summary of estimates of global SOC stocks in topsoil in Pg from different sources

Product	GSOCmap[a]	HWSD[b]	HWSDa[c]	FAO2007[d]	WISE[e]	DSMW[f]	SoilGrids 250m (ISRIC)[g]
SOC stocks (Pg)	680	967	699	710	504	574	1267

Adapted and expanded from Hiederer and Köchy (2011)
[a]GSOCmap (FAO and ITPS 2018)
[b]HWSD—Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009)
[c]HWSDa—Ammended Harmonised World Soil Database (Hiederer and Köchy 2011)
[d]FAO (2007)
[e]WISE (Batjes 2008)
[f]DSMW—Digital Soil Map of the World (FAO-UNESCO 2007)
[g]SoilGrids (http://isric.org/explore/soilgrids)

indicating a high concentration of carbon stocks in the tropical part of Southeast Asia and the Pacific.

The GSOCmap is a product of global efforts to collate existing SOC data from across the world, resulting in a map based on more than one million profiles. This ensures that the GSOCmap is a global product that is consistent with the national soil knowledge and gives the best available estimation of SOC stocks at the country level. The map will be continuously updated as more and better information becomes available. The GSP uses semantic versioning at certain levels to ensure a standard pattern to data releases (FAO and ITPS 2018). The Secretariat publishes the updates and new GSOCmap versions on the Global Soil Partnership website.

The development of the GSOCmap formed part of the process of building a Global Soil Information System (GLOSIS) under GSP Pillar 4, which aims to enhance the quantity and quality of soil data and information. This process paved the way for the establishment of national soil information systems as the foundation of GLOSIS and represents the first step toward introducing a soil monitoring program.

6 Challenges in Managing and Monitoring SOC

The SWSR report (FAO and ITPS 2015) highlighted the most significant threats to soil functions on a global scale, which included the loss of SOC (see Fig. 5a, b). As a result, the ITPS concluded that a priority action should be to stabilize and/or increase the global SOM stocks (e.g., SOC and soil organisms). It further recommended that each nation should identify locally appropriate SOC-improving management practices and facilitate their implementation toward a national-level goal of achieving a stable or positive net SOC balance.

The different land uses and management practices that maintain or increase SOC stocks have simultaneous multiple benefits for achieving food security, mitigation of and adaptation to climate change, protecting biodiversity, and achieving LDN. Although there are many strategies to maintain/increase SOC (control soil erosion, maintain soil cover, apply integrated nutrient management, encourage diversified farming systems, incentivize and empower farmers to manage SOC, and encourage collaboration between scientists, farmers, and policy makers to devise strategies for increasing SOC), the soil responses vary according to the pedoclimatic conditions. It is therefore essential that these practices be selected according to socioeconomic, cultural, and institutional contexts and local farming systems within pedoclimatic regions.

In order to adequately implement sustainable SOC management practices and to guarantee their success, it is necessary to take into account recommendation 3[5] of the Plan of Action for GSP Pillar One and consider the barriers to the adoption of SOC sequestration shown below (FAO 2017b):

- Financial barriers—such as limited finance and access to capital—may discourage farmers from implementing SOC-building practices.
- Technical and logistical barriers may include the unavailability of appropriate technologies, technical capacity or equipment, and the low detectability of short-term changes in SOC stocks.

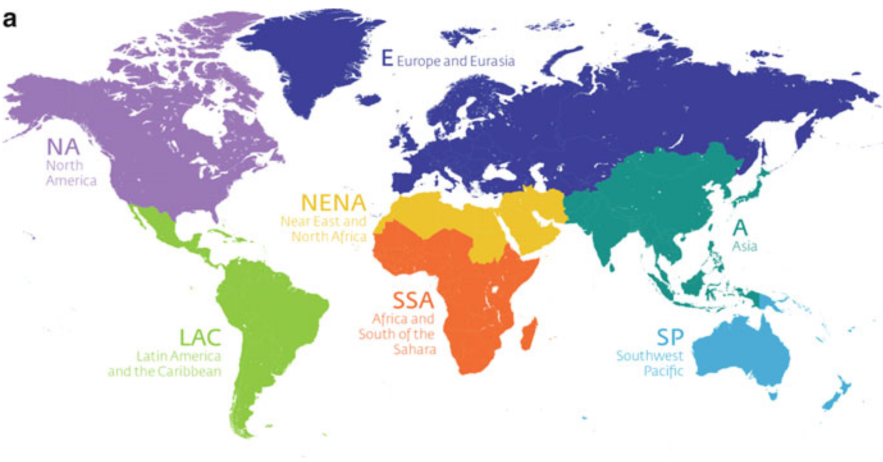

Fig. 5 (**a**) Regions defined by the Global Soil Partnership. (**b**) Summary of the condition and trend for the ten soil threats for the regions (excluding Antarctica). The threats are listed in order of importance

[5]Recommendation 3: All barriers preventing the implementation or adoption of sustainable soil management practices and systems should be assessed and policy and technical solutions proposed to create an enabling environment for sustainable soil management.

b

Threat to soil function	Condition and Trend				
	Very poor	Poor	Fair	Good	Very good
Soil erosion	↙ NENA	↙ A ↙ LAC ↙ SSA	↗ E ↗ NA ↗ SP		
Organic carbon change		↗↙ A ↗↙ E ↙ LAC ↙ NENA ↙ SSA	↗ NA ↗↙ SP		
Nutrient imbalance		↙ A ↗↙ E ↙ LAC ↙ SSA ↙ NA	↙ SP	↗↙ NENA	
Salinization and sodification		↗↙ A ↙ E ↙ LAC	↙ NENA ↗↙ SSA	↗ NA ↗↙ SP	
Soil sealing and land take	↙ NENA	↙ A ↙ E	↗↙ LAC ↙ NA	= SSA ↙ SP	
Loss of soil biodiversity		↙ NENA ↙ LAC	↗↙ A ↙ E ↙ SSA	↗↙ NA ↗↙ SP	
Contamination	↙ NENA	↙ A ↗ E	↗↙ LAC	↙ SSA ↗ NA ↗ SP	
Acidification		↙ A ↗↙ E ↗ SSA ↙ NA	↗↙ LAC ↙ SP	↗↙ NENA	
Compaction		↙ A ↙ LAC ↙ NENA	↗↙ E ↗↙ NA ↗↙ SP	= SSA	
Waterlogging			↙ A ↗↙ E = LAC	↗↙ NENA = SSA ↗↙ NA ↗↙ SP	

Stable = Variable ↗↙ Improving ↗ Deteriorating ↙

Fig. 5 (continued)

- Institutional barriers may take the form of national policies and regulations, insecure land tenure, imperfect markets, limited research and extension services, and weak inter institutional coordination.
- Knowledge barriers may include a lack of information on weather conditions or of management options and their proper implementation. In some cases, it is not so much about the transmission of knowledge to farmers but about who is transmitting it. Information from politically affiliated sources, for example, may be regarded with skepticism, and information from apolitical sources is preferred.
- Resource barriers relate to the absence of sufficient land, labour, inputs, water, or plants to implement climate adaptation and mitigation practices.
- Sociocultural barriers can be cognitive or normative. The way in which farmers perceive climate change and the identification of risks is one of the key barriers influencing people's actions in dealing with climate change mitigation and adaptation.

SOC stocks are temporally and spatially variable, which complicates the sampling, measuring, and monitoring of SOC stocks. Countries place great emphasis on managing, increasing, and monitoring SOC stocks for sustainable development, fostering adaptation to climate change, sustainable agriculture, and restoration of degraded soils. However, quantifying these benefits will not be possible unless changes in C stocks can be measured and monitored accurately and cost-effectively. Accurate SOC measurement and monitoring requires the establishment of baseline SOC stocks from which to measure future changes associated with environmental changes and management.

National monitoring of and reporting on SOC is becoming increasingly important in the fulfillment of global conventions and mechanisms. Under the United Nations Framework Convention on Climate Change (UNFCCC), for example, national SOC stock changes are assessed annually in Annex 1 countries in relation to GHG emissions. Under SDG Indicator 15.3.1,[6] SOC is assessed as one of three subindicators (land cover (metric: land-cover change), land productivity (metric: net primary productivity), and carbon stocks above and below ground (metric: SOC)) in accordance with the UNCCD's LDN concept. Countries therefore need easy-to-use guidelines to measure and monitor SOC stocks and stock changes over time.

7 Unlocking the Potential of SOC: Priorities for Action

The GSOC17 outcome document provides eight key recommendations (Table 3) to support the global SOC agenda through the development of policies and actions that foster the protection, sequestration, measurement, mapping, monitoring, and

[6]SDG Indicator 15.3.1: Proportion of land that is degraded over total land area.

Table 3 Recommendations from GSOC17

Recommendation 1	Organize capacity development and training for countries to develop national reference values for SOC stocks, as well as the necessary data management capacities and facilities.
Recommendation 2	Establish a working group to develop feasible and regionally contextualized guidelines for measuring, mapping, monitoring and reporting on SOC that can be adapted locally to monitor SOC stocks and stock changes to support management decisions.
Recommendation 3	In estimates of the potential for SOC sequestration, include the full GHG balance and consider possible interactions between the carbon and nitrogen cycles that could affect the climate change mitigation potential of applied practices.
Recommendation 4	The design of implementation strategies and appropriate soil and land management practices for SOC protection and sequestration should consider land use and the local environmental, socio-economic, cultural and institutional contexts, and potential barriers to adoption.
Recommendation 5	Identify and specify the tangible short-term and long-term benefits for farmers of management practices for SOC sequestration to trigger their adoption and introduce mechanisms to incentivize the adoption of such practices.
Recommendation 6	Prevent SOC losses by maintaining current SOC stocks (especially in carbon-rich soils) as the minimum action on SOC management.
Recommendation 7	Prioritize soils with the highest carbon stocks in the development of national and regional policies on soil conservation to prevent SOC losses.
Recommendation 8	Support land-users sufficiently to implement and sustain appropriate soil and land management practices to protect and enhance SOC under local conditions for long-term benefit.

reporting of SOC. It was established that the main priority is to prevent further SOC losses and, where feasible, increase SOC stocks. Implementation of these recommendations has commenced through various activities, as described in the following subsections.

7.1 Technical Manual on SOC Management

In view of the urgency to identify, compile, and highlight management practices and land use systems that promote the preservation and/or enhancement of SOC stocks, the ITPS and GSP Secretariat issued a call for experts to join a working group (WG) to develop a technical manual on SOC management at regional and subregional scales. This technical manual would refine the recommendations in the Voluntary Guidelines for Sustainable Soil Management (VGSSM) (FAO 2017c) in terms of sustainable SOC management at the regional, national, and local scales to consider site-specific conditions (i.e., climate, soil type, land use, farm typology, etc.).

More than 200 experts from around the world joined the WG, of which 130 experts are actively participating. An electronic communication process is used by lead authors to compile and recommend management practices and actions for the preservation and/or enhancement of SOC. These recommendations will be divided by major land use systems as (a) unmanaged and protected lands (including virgin forests, rangelands, grassland, shrublands, wetlands, sparse and bare areas); (b) forestry (managed/silviculture, with agricultural or livestock activities: agroforestry, silvopastoral systems); (c) grassland, shrublands, and bare and sparse areas with low, moderate, and high livestock density; (d) rain-fed agriculture (subsistence, familiar, and commercial); (e) irrigated agriculture; (f) rain-fed or irrigated agriculture with livestock; (g) wetlands with agricultural activities; and (h) urban areas.

The recommendations will be based on scientific evidence with the best management practices and systems that promote the preservation and, wherever possible, the increase of SOC stocks in all land uses at regional, subregional, and national levels. These contributions should be adapted to site characteristics and land user needs and consider cost-benefit analyses and social impacts. The priorities of action, as reflected in the Regional Implementation Plans of the Regional Soil Partnerships, will be thoroughly taken into account.

The inputs generated will contribute significantly to GSOC17 recommendations 3, 4, 5, 6, and 8 (from Table 3). These recommendations focus on including the full GHG balance and considering possible interactions between the C and N cycles, identifying appropriate soil and land management practices for SOC protection and sequestration and potential barriers for adoption, identifying and specifying the tangible short-term and long-term benefits for farmers of management practices, preventing SOC losses, and supporting land users to implement relevant practices. The WG inputs will be compiled as a technical manual on SOC management, as outlined in Table 4, to be published and launched by the GSP Secretariat during the World Soil Day 2018.

7.2 Guidelines for Measuring, Mapping, Monitoring, and Reporting on SOC

Recommendation 2 of GSOC17 (Table 3) calls for the establishment of a WG to develop feasible and regionally contextualized guidelines for measuring, mapping, monitoring, and reporting on SOC. These guidelines should be adaptable to local conditions to monitor SOC stocks and stock changes to support management decisions.

The GSP Secretariat launched an open call for a WG to develop these guidelines, which need to build on existing scientific guidance, such as the IPCC guidelines for national GHG inventories, which are being refined (IPCC 2006). Furthermore, the guidelines should be simple enough to enable implementation in diverse contexts and scales, as well as different local and national capacities and capabilities in countries. Practical guidance should include elements to support carbon-pricing mechanisms by relying on the measurement of SOC stocks to assess stock changes,

Table 4 Working structure of the technical manual on SOC management

Chapter		Considerations
1	Introduction and preparation process of the technical manual.	
2	Points of consideration when studying, recommending and adopting sustainable soil management practices that target the preservation and/or enhancement of SOC.	Consider the possible trade-offs of SOC sequestration efforts when assessing the full GHG balance. Discuss: the required efforts to measure and monitor SOC stocks; the link between SOC and soil inorganic carbon; the co-benefit analysis of SOC sequestration in SOM and soil quality improvement; and nutrient use efficiency for better GHG balance and better water quality.
3	Recommended management practices and actions for preservation and/or enhancement of SOC.	Consider the local environmental, socio-economic, cultural and institutional contexts, and potential barriers to adoption. Include case studies and success stories of effective practice adoption and achieved SOC/SOM preservation/increase whenever suitable, as long as studies are based on measurements and evidence-based results with adequate statistical accuracy.
3.1	Unmanaged and Protected Lands.	Including virgin forests, rangelands, grasslands, shrublands, wetlands, sparse and bare areas.
3.2	Forestry.	Managed/silviculture.
3.3	Forestry with agricultural or livestock activities.	Agroforestry, silvopastoral systems.
3.4	Grasslands, shrublands, and bare and sparse areas with low, moderate, and high livestock density.	
3.5	Rainfed agriculture.	Subsistence and familiar.
3.6	Rainfed agriculture.	Commercial.
3.7	Irrigated agriculture.	
3.8	Rainfed or irrigated agriculture with livestock.	
3.9	Urban areas.	
3.10	Wetlands with agricultural activities.	
4	Experiences with diverse incentivizing mechanisms for large scale practice adoption.	
5	Future directions and identified gaps.	

rather than using only stock change factors based on land use and management practices.

The guidelines are expected to be widely implemented, and the process will be supported by the GSP Capacity Development Programme and technical manuals.

The guidelines shall be a milestone to establish a global SOC-monitoring network as part of GLOSIS.

7.3 International Network of Black Soils (INBS)

Recommendation 6 of GSOC17 calls for the prevention of SOC losses, especially in carbon-rich soils. Black soils (BSs) constitute an important group of carbon-rich soils that are particularly important globally because of their relevance to food security and climate change mitigation. In view of their inherent high fertility, BSs remain very sensitive to anthropogenic intervention and are prone to severe degradation. Because of their high SOC content, they are also very sensitive and can be potential large sources of GHGs. Extensively and intensively farmed, they constitute the food basket for many countries. Notwithstanding the relatively small percentage (7%) of the world's ice-free land surface covered by BSs, it is crucial to promote their conservation and sustainable use to maintain their functioning in order to sustain their supporting food security while protecting the environment and mitigating climate change.

The International Network of Black Soils (INBS) was established under the aegis of the GSP to provide a platform for knowledge sharing for countries with BSs to discuss common issues related to the conservation and sustainable management of these soils and the need to foster technical exchange and cooperation. The INBS was launched during GSOC17 with representatives from national soil institutions from Argentina, Brazil, China, Russian Federation, and the USA. Then network will foster collaboration among countries with BSs that will identify relevant research gaps to be addressed in a report on the global status, the current productivity, and the challenges in BSs.

Given the different perceptions of BSs, a formal definition of this group of soils will be developed under the INBS. In this definition, priority will be given to Chernozems, Kastanozems, and Phaeozems based on World Reference Base (WRB) classification and Mollisols of US soil taxonomy.

The crop output of black soils in areas such as the USA Corn Belt, Northeast China, and Ukraine has been increasing dramatically and dominated food production enhancement at a global scale during the past two decades. This was mainly due to the high fertility of black soils and the intensive farming practices used (Liu et al. 2012). However, black soil regions are facing serious soil degradation such as erosion, acidification, and decreasing SOM content (Russell et al. 2005; Kharytonov et al. 2004). Higher SOC content is a fundamental soil property that is easily lost when agriculture is introduced. For example, average SOC of black soils in Northeast China of 100 g kg^{-1} under natural conditions could be decreased by half after land reclamation or continually decline if inappropriate farming management is used (Gollany et al. 2011; Zhao et al. 2013). Declining SOC not only negatively impacts soil productivity but is also an important factor in climate change because of its large potential for GHGs emission (Lal 2004). Therefore, maintaining or improving the SOC content of black soil is crucial for global sustainable agriculture development.

Increased awareness among policy makers and relevant stakeholders in black soil countries is essential to highlight the key role of SOC in the sustainable management and development of black soils. It is envisaged that the INBS will serve to provide such awareness, backed up by scientific evidence.

8 Conclusions and Way Forward

Responding to a request for support in measuring SDG indicators 15.3.1, the GSOCmap was the first-ever global map produced through a consultative, participatory, and country-driven process. This process involved FAO member countries under the guidance of the ITPS and the GSP Secretariat to ensure a thorough harmonization process. This huge effort represents an essential step to better understanding SOC stocks and their potential for further sequestration, as well as enabling countries to collect and compile national SOC data and information for future monitoring.

The Outcome Document offers an overview of the state-of-the-art in SOC monitoring and presents specific recommendations in order to promote the preservation and, wherever possible, the increase of SOC stocks in all land uses at all levels. These recommendations have resulted in the implementation of concrete actions such as the creation of working groups to develop feasible and regionally contextualized guidelines for measuring, mapping, monitoring and reporting on SOC and for producing a technical manual on SOC management at regional and sub-regional scales. These actions are being developed through the active participation of the working groups and it is expected that both the guidelines and the technical manual will be launched by the GSP Secretariat on World Soil Day (December 2018). Regarding the INBS, the International Symposium on Black Soil (ISBS18) will soon be held in Harbin, China (September 2018). Some of the most important inputs will be: the establishment of a global status report of black soil; the establishment of a good practices database; the implementation of efficient management practices; and a policy-oriented document based on scientific evidence showing the pathways toward the implementation of sustainable soil management which would highlight success stories and technological innovations in black soil regions.

Once these activities are completed, the next challenge is to implement actions to promote the practice of SSM concerning soil carbon sequestration. In this regard, the GSP proposed to establish a global SOC monitoring system, establish a global map of SOC sequestration potential, and to implement the technical manual on SOC management (identifying key regions for pilot projects).

References

Amundson R, Berhe AA, Hopmans JW, Olson C, Sztein AE, Sparks DL (2015) Soil and human security in the 21st century. Science 348(6235). https://doi.org/10.1126/science.1261071

Batjes NH (2008) ISRIC-WISE Harmonized Global Soil Profile Dataset (ver. 3.1). Report 2008/02. ISRIC – World Soil Information, Wageningen, The Netherlands, 52 pp

Batjes NH (2014) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 65(1):10–21. https://doi.org/10.1111/ejss.12114_2

Crowther TW, Todd-Brown KEO, Rowe CW, Wieder WR, Carey JC, Machmuller MB, Snoek BL, Fang S, Zhou G, Allison SD, Blair JM, Bridgham SD, Burton AJ, Carrillo Y, Reich PB, Clark JS, Classen AT, Dijkstra FA, Elberling B, Emmett BA, Estiarte M, Frey SD, Guo J, Harte J, Jiang L, Johnson BR, Kröel-Dulay G, Larsen KS, Laudon H, Lavallee JM, Luo Y, Lupascu M, Ma LN, Marhan S, Michelsen A, Mohan J, Niu S, Pendall E, Peñuelas J, Pfeifer-Meister L, Poll C, Reinsch S, Reynolds LL, Schmidt IK, Sistla S, Sokol NW, Templer PH, Treseder KK, Welker JM, Bradford MA (2016) Quantifying global soil carbon losses in response to warming. Nature 540:104–110

De Graaf MA, Adkins J, Kardol P, Throop HL (2015) A meta-analysis of soil biodiversity impacts on the carbon cycle. Soil 1:257–271

Deb S, Bhadoria PBS, Mandal B, Rakshit A, Singh HB (2015) Soil organic carbon: towards better soil health, productivity and climate change mitigation. Clim Change Environ Sustain 3 (1):26–34

FAO (2007) The digital soil map of the world. Food and Agriculture Organization of the United Nations. Version 3.6, completed January 2003 and updated 2007

FAO (2015) Revised World Soil Charter. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/a-i4965e.pdf

FAO (2017a) Soil organic carbon: the hidden potential. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/a-i6937e.pdf

FAO (2017b) Unlocking the potential of soil organic carbon, outcome document of the global symposium on Soil Organic Carbon. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/b-i7268e.pdf

FAO (2017c) Voluntary guidelines for Sustainable Soil Management. Food and Agriculture Organization of the United Nations, Rome

FAO (2018) Plan of action for pillar one of the global soil partnership. http://www.fao.org/3/a-az898e.pdf

FAO and GSP (2016) Report of the fifth working session of the Intergovernmental Technical Panel on Soils. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/3/a-bl137e.pdf

FAO and ITPS (2015) Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome

FAO and ITPS (2018) Global Soil Organic Carbon Map (GSOCmap) Technical Report. Food and Agriculture Organization of the United Nations, Rome

FAO/IIASA/ISRIC/ISSCAS/JRC (2012) Harmonized World Soil Database (version 1.2). FAO/IIASA, Rome/Laxenburg

FAO/IIASA/ISRIC/ISS-CAS/JRC (2009) Harmonized World Soil Database (version 1.1). FAO/IIASA, Rome/Laxenburg

FAO-UNESCO (2007) Digital Soil Map of the World, Land and Water Development Division. FAO, Rome

Field CB, Raupach MR (2004) The global carbon cycle. Integrating humans, climate, and the natural world. Island Press, Washington DC, 526 pp

Gardi C, Jeffery S (2009) Soil biodiversity. Joint Research Center: Institute for Environment and Sustainability, Luxembourg

Gaudinski J, Trumbore S, Davidson E, Zheng S (2000) Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning if fluxes. Biogeochemistry 51:33–69

Gollany H, Rickman RW, Liang Y, Albrecht SL, Machado S, Kang S (2011) Predicting agricultural management influence on long-term soil organic carbon dynamics: implications for biofuel production. Agron J 103(1):234–246

Gougoulias C, Clark JM, Shaw LJ (2014) The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. J Sci Food Agric 94:2362–2371

Hiederer R, Köchy M (2011) Global soil organic carbon estimates and the Harmonized World Soil Database, JRC Scientific and Technical Reports, 68528/EUR 25225 EN, Joint Research Centre, Ispra, Joint Research Centre. https://doi.org/10.2788/13267

IPCC (2006) 2006 IPCC guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme. Volume 4 Agriculture, forestry and other land use. Intergovernmental Panel on Climate Change (IPCC). http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

IPCC (2014) Climate Change 2014: Synthesis, Report Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva

Janzen HH, Campbell CA, Brandt SA, Laford GP, Townley-Smith L (1992) Light-fraction organic matter in soils from long-term crop rotations. Soil Sci Soc Am J 56:1799–1806

Jobbagy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10:423–436

Keesstra SD, Bouma J, Wallinga J, Tittonell P, Smith P, Cerdà A, Montanarella L, Quinton JN, Pachepsky Y, Van der Putten WH, Bardgett RD, Moolenaar S, Mol G, Jansen B, Fresco LO (2016) The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. Soil 2:111–128

Kharytonov M, Bagorka M, Gibson PT (2004) Erosion effects in the central steppe chernozem soils of Ukraine. I. Soil properties. Agricultura 3(1):12–18

Kochy M, Hiederer R, Freibauer A (2015) Global distribution of soil organic carbon. Part 1: masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. Soil 1(1):351–365. https://doi.org/10.5194/soil-1-351-2015

Lal R (2002) The potential of soils of the tropics to sequester carbon and mitigate the greenhouse effect. Adv Agron 76:1–30

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science. 304:1623–1627

Liu X, Burras CL, Kravchenko YS, Duran A, Huffman T, Morras H, Studdert G, Zhang X, Cruse RM, Yuan X (2012) Overview of Mollisols in the world: distribution, land use and management. Can J Soil Sci 92:383–402

Lorenz K, Lal R (2016) Soil organic carbon – an appropriate indicator to monitor trends of land and soil degradation within the SDG Framework? Section II 2.9 Rural development, agriculture and international soil protection, Sue Martina Starke, Knut Ehlers. ISSN 1862-4804

Orgiazzi A, Bardgett RD, Barrios E, Behan-Pelletier V, Briones MJI, Chotte J-L, De Deyn GB, Eggleton P, Fierer N, Fraser T, Hedlund K, Jeffery S, Johnson NC, Jones A, Kandeler E, Kaneko N, Lavelle P, Lemanceau P, Miko L, Montanarella L, Moreira FMS, Ramirez KS, Scheu S, Singh BK, Six J, Van der Putten WH, Wall DH (2016) Global Soil Biodiversity Atlas. European Commission, Publications Office of the European Union, Luxembourg

Russell AE, Laird DA, Parkin TB, Mallarino AP (2005) Impact of nitrogen fertilization and cropping system on carbon sequestration in midwestern Mollisols. Soil Sci Soc Am J 69:413–422

Scharlemann PWJ, Tanner VJE, Hiederer R, Kapos V (2014) Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag 5(1):81–91. https://doi.org/10.4155/cmt.13.77

Schlesinger WH (1997) Carbon balance in terrestrial detritus. Ann Rev Ecol Syst 8:51–81
Schlesinger W, Bernhardt E (2013) Biogeochemistry: an analysis of global change, 3rd edn. Academic, San Francisco
Schmidt M, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knabner I, Lehmann J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. Nature 478:49–56
Six J, Conant R, Paul E, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176
Sohi S, Mahieu N, Arah J, Powlson D, Madari B, Gaunt J (2001) A procedure for isolating soil organic matter fractions suitable for modeling. Soil Sci Soc Am J 65:1121–1128
Thiele-Brunh S, Bloem J, de Vries FT, Kalbitz K, Wagg C (2012) Linking soil biodiversity and agricultural soil management. Environ Sustain 4:523–528
Van der Wal A, De Boer W (2017) Dinner in the dark: illuminating drivers of soil organic matter decomposition. Soil Biol Biochem 105:45–48
Wall DH, Nielson UN, Six J (2015) Soil biodiversity and human health. Nature 528:69–76
Weissert L, Salmond JA, Schwendenmann L (2016) Variability of soil organic carbon stocks and soil CO2 efflux across urban land use and soil cover types. Geoderma 271:80–90
Yigini Y, Olmedo GF, Reiter S, Baritz R, Viatkin K, Vargas R (eds) (2018) Soil organic carbon mapping cookbook, 2nd edn. FAO, Rome, 220 pp
Zhao G, Bryan BA, King D, Luo Z, Wang E, Song X, Yu Q (2013) Impact of agricultural management practices on soil organic carbon: simulation of Australian wheat systems. Glob Chang Biol 19(5):1585–1597