CHAPTER

SOIL CARBON: INTRODUCTION, IMPORTANCE, STATUS, THREAT, AND MITIGATION

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1.1 INTRODUCTION

The world is facing multiple challenges including food security, environmental sustainability, soil protection, and climate change. These challenges need to be tackled as a priority to avoid human-made catastrophe in coming decades (Banwart et al., 2014a,b) and to double farm productivity by 2050 to feed ~9.6 billion people (Lal, 2006; Alexandratos and Bruinsma, 2012). This increase in farm productivity needs to come from shrinking arable lands (Singh and Trivedi, 2017), where one-third of food production has been lost due to reduction in soil organic carbon (SOC) and land degradation, hence requiring management improvements to restore C-poor degraded lands (Hazell and Wood, 2008; Brevik, 2010; Pimentel and Burgess, 2013). In addition to advancing food security, soil resources need to be managed in sustainable ways to meet multiple global needs, including mitigating and adapting to climate change, improving the quality and quantity of water resources, promoting biodiversity, preserving human heritage, preventing desertification, alleviating poverty, and being an engine of new industries and economic growth (Lal, 2007).

SOC is a critical natural resource and contributes significantly to achieving all these goals, such as by directly storing more C in soils, while improving soil health and ecosystem functions. SOC is considered a key indicator for soil health because of its contributions to food production, mitigation and adaptation to climate change, and role in water storage and purification. The SOC content is almost 50% − 58% of soil organic matter (SOM) (Pribyl, 2010), which stores nutrients for plants, improves soil structural stability to enhance soil fertility, and ultimately provides food. With an optimal amount of SOC, the filtration capacity of soils further supports the supply of clean water. Turnover of SOC in terrestrial ecosystems is dynamic and human impacts can turn SOC into either a net sink or a net source of greenhouse gases (GHG) to the atmosphere. Although the overall impact of climate change on SOC stocks is highly variable according to the region and soil type, rising temperatures and increased frequency of extreme drought events are likely to lead to increased loss of SOC. Significant scientific progress has been achieved in understanding and explaining SOC dynamics. The dynamics of these processes highlight the importance of quantifying global C fluctuations to ensure maximum benefits of SOC to human well-being, food production, and water and climate regulation. However, protection and monitoring of SOC stocks at national

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and global levels still face complicated challenges impeding effective on-the-ground policy designs and regionally adapted implementation. This chapter highlights the importance of SOC for ecosystem services and intergovernmental policies. Further, this chapter describes the potential and challenges of soil C sequestration and how knowledge of SOC dynamics can be applied to address multiple global challenges and deliver ecosystem benefits within increasingly complex policy frameworks (see Box 1.1 for definitions).

1.1.1 CARBON CYCLE

The carbon (C) cycle consists of the transfer of C in different forms between the atmosphere, living organisms (biosphere), and soil (pedosphere) (Orgiazzi et al., 2016). The current level of atmospheric CO_2 concentration is a balance between C fixation *via* photosynthesis and C loss via respiration. In terrestrial systems, about 123 Gigaton (Gt) of C is assimilated by primary production and about 120 Gt are respired back roughly half by autotrophic respiration and another half by microbial respiration (Högberg et al., 2001; Nordgren et al., 2003; Singh et al., 2010) (Fig. 1.1). Human activities have significantly modified the global C cycling by enhancing the release of significant CO_2 through fossil fuel burning and industrial activities. About 9 Gt are added in the atmosphere by

BOX 1.1

Definition of soil: Soil is a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment (Soil Science Society of America, 2017).

Definition of soil health: Soil health is the capacity of soil to function as a living system, within ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production. A healthy soil prevents pollution of environment and contributes to mitigating climate change by maintaining or increasing its carbon content (Doran and Zeiss, 2000; FAO and ITPS, 2015).

Definition of soil quality: Soil quality can be defined as the fitness of a specific kind of soil, to function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen et al., 1997; Arshad and Martin, 2002). Many times, soil quality is used as synonymous to soil health.

Definition of ecosystem functions: Ecosystem functions (sometimes called as ecological processes) relate to the structural components of an ecosystem (e.g., vegetation, water, soil, atmosphere, and biota) and how they interact with each other, within an ecosystem and across ecosystems. Primarily, these are exchanges of energy and nutrients in the food chain which are vital to the sustenance of plant and animal life on the planet as well as the decomposition of organic matter and production of biomass made possible by photosynthesis (Tilman et al., 2014).

Definition of ecosystem services: Ecosystem services is the technical term given to the goods and services provided by the ecosystem that directly benefits, sustain and support the well-being of people (Guerry et al., 2015).

Definition of soil organic matter (*SOM*): As per a new paradigm, SOM is a continuum of progressively decomposing organic compounds of plant, animal, and microbial origin that are stabilized with clay minerals and soil aggregates through microbial, physical, and chemical processes (Lehmann and Kleber, 2015).

Definition of soil organic carbon (*SOC*): SOC is a measure of carbon contained within SOM. SOM usually contains approximately 58% C; therefore, a factor of 1.72 can be used to convert OC to SOM.

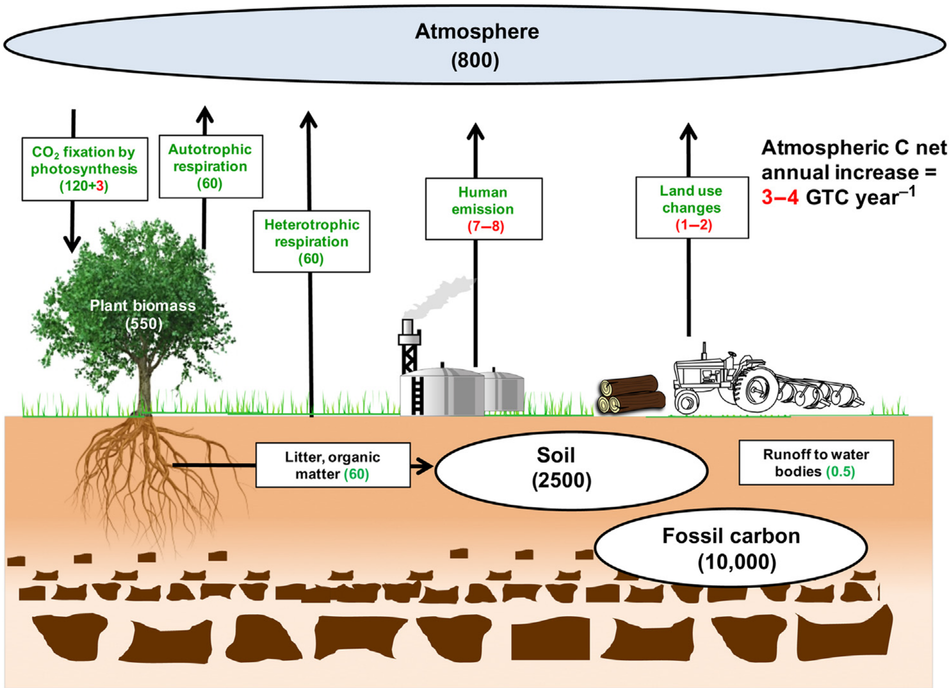

FIGURE 1.1

Simplified terrestrial carbon cycle. The values in bracket of square boxes represent the exchange of C between land and atmosphere in Gigatons (Gt) of C per year. Green numbers are natural fluxes; red numbers are human contributions (Gt of C per year). The values in bracket in oval indicate the amount of C in different pools (Gt).

human activities consisting of 7–8 Gt from the fossil fuel burning and 1–2 Gt via land-use change primarily via deforestation (Fig. 1.1). The current global C budget is thus unbalanced due to higher CO_2 emission into the atmosphere than C sink in soil and vegetation, mainly driven by human activities. House et al. (2003) reported that terrestrial C uptake was in the range of 0.3–4.0 Gt C year^{-1} and 1.6–4.8 Gt C year^{-1} for the 1980s and 1990s, respectively. Le Quéré et al. (2015) presented a new estimate of the present-day global carbon budget and pointed out that on average 45% of the total CO_2 emitted from anthropogenic activities (mainly fossil fuel burning and land use change) stayed in the atmosphere in the past decades. They also suggested that the efficiency of C sinks could have decreased in the past decades. This creates an unbalanced global budget and has led to a sustained increase of atmospheric CO_2 concentration, the main driver of global warming. The further consequences of this imbalance in C budget are unpredictable feedback responses of climate change (detailed in Chapter 8: Impact of Global Changes on Soil C Storage—Possible Mechanisms and Modeling Approaches). Understanding the global C cycle and how it interacts with climate change is a key research challenge that is crucial for the future of our planet.

The process of C sequestration includes CO_2 fixation, transfer of fixed C to plant biomass and soils, and stabilization of organic C in soil where it is stored as SOC following interactions with soil microbes, minerals, and aggregates. Terrestrial C sequestration, with application of improved management methods (see Chapter 7: Agricultural Management Practices and Soil Organic Carbon Storage), could sequester more than 0.5 Gt C $year^{-1}$ by 2040 mitigating from 6% to 23% of the emissions by mid-century and accumulating over 40 Gt of C by 2100 (Thomson et al., 2008; Post et al., 2009). Increased SOC storage occurs via multiple factors that result in increased C inputs and reduced C losses (or both) and is influenced by soil texture, clay mineralogy, depth, bulk density, aeration, and proportion of coarse fragments (see Chapter 5: Climate, Geography and Soil Abiotic Properties as Modulators of Soil C Storage for details). Carbon residence time is a key factor affecting C sequestration potential in different soils (Post et al., 2009; Luo et al., 2015). Interactions with minerals can provide physicochemical protection of C that is determined by processes responsible for creation, turnover, and stabilization of soil aggregates at multiple, often hierarchical scales (Tisdall and Oades, 1982; Jastrow and Miller, 1997; Six et al., 2004). These stabilization mechanisms operate at different time scales (Lützow et al., 2006), and their interactions lead to a continuum of SOC pools with residence times that can range from less than a year to centuries and even millennia (Post et al., 2009). Furthermore, the effectiveness and relative importance of different factors related to C stabilization depends on various factors, including soil type, management practices, historical contingency, and climate conditions (Post et al., 2009; Delgado-Baquerizo et al., 2017b).

1.2 HUMAN CIVILIZATIONS AND SOIL ORGANIC CARBON

Since the dawn of human civilization, SOM and SOC have been recognized as a key to manage soil fertility and improving agronomic productivity. This topic is well covered in previous publications (Lal, 2007, 2014, 2016). Briefly, the words "human" and "humus" (mixture of dark, colloidal poly-dispersed organic compounds with high molecular weights and relatively resistant to decomposition) are intricately linked and SOM has been considered by ancient civilizations to be a "concoction" of sustainability and productivity (Lal, 2016). Archeologists have identified examples of human societies that have been brought to the limit of sustainability by SOM/SOC depletion, even resulting, in some cases, in the decline and fall of their civilization (Olson, 1981; Fig. 1.2). The experiences of past societies provide ample historical basis for linking soil quality to SOM/SOC and long-term prospects of managing SOM/SOC for multiple societal benefits (Lal, 2016). For example, Asian farmers were able to cultivate the same field for as long as 40,000 years by maintaining soil fertility and managing SOM/SOC via manuring and recycling (Lal, 2014). A Sanskrit text written in about 1500 BC quoted: "Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it and the soil will collapse and die, taking humanity with it (Shiva et al., 2016)." Agronomic functions of SOM/SOC and their connection to cropping and farming sustainability has been recognized and preached by the philosophers and religious leaders from ancient times. In 1400 BC, after their arrival in Canaan, Moses asked his followers to "bring back some fruits from lands with fertile soils as those represent healthy people" (Lal, 2016). In the 4th century BC, an Indian Scholar, Chanukya/Kautilya in his manual *Artha Sathra* encouraged land managers to improve soil functions by applying manure and proposed mechanisms to manage soil fertility and water conservation. In

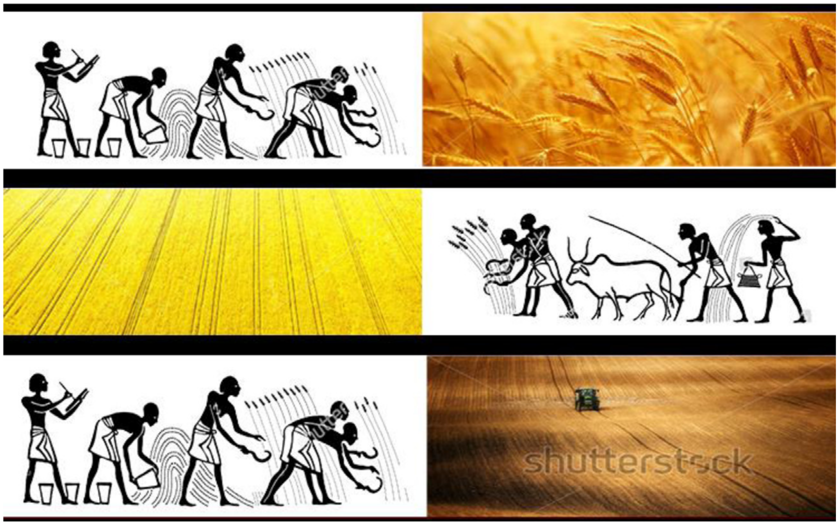

FIGURE 1.2

Drawing illustrates linkage between soil and human civilizations (particularly farming). All through human civilization, soil organic matters and soil organic carbon have been recognized as key manage soil health and farm productivity.

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middle history around 12th century, a Moorish philosopher, Ibn-Al-Awwam stated in his book *Kitab-Al-Felha* that the first step of agriculture is recognition of soils and how to distinguish that which is of a good quality and that which is of an inferior quality (Lal, 2016).

In modern civilization, the role of SOM/SOC in controlling the capacity of soil resources to deliver agricultural and environmental services and sustain human societies at both local (e.g., fertility maintenance) and global (e.g., mitigation of atmospheric C emissions) scales is well established (Tiessen et al., 1994; Wolf and Snyder, 2003). Emphasizing the importance of agronomic practices that increase SOM, MK Gandhi wrote “to forget how to dig the earth and to tend soil is to forget ourselves.” U.S. President Franklin D. Roosevelt, who in 1935 signed legislation aimed at combating soil erosion and preserve natural resources, made a powerful statement on the importance of maintaining soil quality by stating: “A nation that destroys its soils destroys itself.” Increasingly, farmers, scientists, landowners, environmental experts, and policymakers understand that SOM/SOC management is critical in order to improve soil health and that addressing its complex challenges is urgently required to meet global concerns including food security, climate change mitigation, and water conservation (Doran et al., 1994; Lal, 1997, 2016). Innovative initiatives by government and intergovernmental agencies such as United States Department of Agriculture (USDA), Food and Agriculture Organization (FAO), USDA, FAO, Global Soil Partnerships (GSP), United Nations Convention to combat Desertification (UNCCD), and United Nations Environmental Program (UNEP), as well as newer public−private entities such as the Soil Health Partnership, the Global Soil Biodiversity Initiative, and the Soil Health Institute (in United States), are already making important progress in coordinating, innovating, and investing to monitor the status, threats, and propose mitigation/agronomic approaches to build SOC. A notable change is underway, and momentum is increasing around the opportunity to manage SOC to address important social and environmental challenges.

1.3 HEALTHY SOIL IS THE FOUNDATION FOR ECOSYSTEM SERVICES AND TERRESTRIAL LIFE

Healthy soil is the cornerstone of terrestrial life on Earth, providing habitat for biodiversity, facilitating food production, effective water filtration and storage, and regulating the climate. It is fundamental to soil fertility by retaining and releasing nutrients for plant growth. Plants being the primary producers, capture C from the atmosphere, energy from sunlight, and transfer the photosynthesized C to soil for growth and activities of other organisms (heterotrophs) via root exudation and litter deposition. These forms of SOM are then recycled by heterotrophs (microbes and fauna) into different forms of soil C, which interact with soil minerals and microbes, and release nutrients (e.g., nitrogen, phosphorus, and sulfur) from SOM turnover to support plant growth. In healthy "functional" soils, SOC is a basis of critical physicochemical and biological processes (Lal, 2014) and it drives almost all key services that underpin the role of healthy soils in maintaining terrestrial life (Fig. 1.3).

All aspects of humanity, including peace and war, rural and urban setting, poverty and affluence, can be affected by soil health (Keesstra et al., 2016). Although advancement in agriculture technology throughout the past century has increased food production, their wide-scale application has significantly reduced soil quality with a loss of as much as 60% in SOC content (Lal, 2004). The degradation of soils has undermined the productivity and resilience of croplands while causing significant environmental impacts resulting in increased GHG emissions, nutrient loss, and soil erosion. In 2015, a report estimated that in the United States alone, the societal and environmental cost of soil degradation is up to $85.1 billion annually through unintended effects on human health, property, energy, endangered species, loss of biodiversity, eutrophication, contamination, agriculture productivity, and resilience. As highlighted in the first principle established by the revised World Soil Charter (FAO, 2015, p. 2): "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, fiber, and fuel production required to achieve food and energy security will place increased pressure on the soil." The 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development which were adopted by world leaders in September 2015 explicitly identified the need to restore degraded soils and improve soil health.

Maintaining SOC stock at an equilibrium or increasing SOC content toward an optimal level for the local environment can contribute to meeting several global challenges including: (1) Provision of food and energy for soil biodiversity to further improve nutrient availability for plant uptake, and support productivity of aboveground plants and animals; (2) Ensuring chemical reaction, transformation and exchange for ensuring optimal nutrient and water availability; (3) Improving soil physical structure for optimal provision of habitats and exchange of air, water, and gases; and (4) Mitigating climate change effects by C sequestration and offsetting GHG emissions.

1.4 SOIL ORGANIC CARBON IS THE MOST IMPORTANT COMPONENT OF SOIL QUALITY AND HEALTH

Soil organic C is critical to soil health and a threshold/critical level of 1.5%−2.0% of SOC in agroecosystems is proposed as essential to maintain: (1) Appropriate soil structure and aggregates; (2) Water retention, release and use efficiency and resilience to abiotic stresses—e.g., drought, heat wave; and (3) Nutrient retention, release and use efficiency and gas exchanges to regulate climate change (Banwart et al., 2014a,b). Soil organic C is typically segregated into distinct "pools" or "fractions" with unique characteristics and specific turnover times (Parton et al., 1994). These pools have been used to indicate the sustainability of farming practices from a soil quality or C sequestration perspective and include plant residues, particulate organic matter (POM), humus C, and recalcitrant organic C. The POM fraction (Cambardella and Elliott, 1992) is a fraction of SOM that is composed of particulate (>0.05 mm), partially decomposed plant and animal residues, fungal hyphae, spores, root fragments, and seeds (Causarano et al., 2008). The POM fraction provides an important energy source for soil microbes, and the proportion of organic matter in this fraction can be directly correlated with soil fertility (Lehman et al., 2015). Soil microbial biomass C and potentially mineralized C are considered as active fractions of SOM and are important for supplying plant nutrients, decomposing organic residues, and developing soil structure (Franzluebbers and Stuedemann, 2008). These fractions together with POM and soil aggregation are important indicators of dynamic soil quality because they are responsive to change in management practices (Franzluebbers, 2002; Causarano et al., 2008). The recalcitrant pool is of utmost interest for C sequestration as an option of mitigating climate change given its ability to resist rapid decomposition, but is also important for the chemical health of soil by its influence on cation exchange capacity (CEC). Different soil management practices are known to alter not only total SOC, but also the relative proportion of C residing in these different pools. For example, management practices that produce high amounts of organic materials such as pastures and native vegetation will have higher proportions of residue and POM. On the other hand, agricultural systems characterized by continuous cropping, long fallow periods, tillage, and stubble burning or grazing typically have low proportions of these, relatively labile, C fractions. Knowledge of how C pools/fractions change in response to management can provide valuable information on likely soil functioning and health (See Chapter 2: Plant Communities as Modulators of Soil Carbon Storage, Chapter 7: Agricultural Management Practices and Soil Organic Carbon Storage, and Chapter 8: Impact of Global Changes on Soil C Storage—Possible Mechanisms and Modeling Approaches for more details). It must also be noted that in recent years however the long-standing theory that suggests that SOM is composed of inherently stable and chemically unique compounds has been challenged and a "continuum model" that suggests that SOM is a continuum of progressively decomposing organic compounds has been proposed (Lehmann and Kleber, 2015).

1.5 SOIL ORGANIC CARBON IS A MAJOR DRIVER OF ECOSYSTEM SERVICES

Ecosystem functions include the physicochemical and biological processes that occur within the ecosystem to maintain terrestrial life. Ecosystem services are the set of ecosystem functions that are directly linked to benefit human well-being (Kremen, 2005). Soil organic C regulates most ecosystem services including provisioning, supporting, regulating, and cultural services (Fig. 1.3). These ecosystem services can be broadly categorized as: (1) Provisioning services—SOM serves as the basis for food and fiber production via influencing soil structure, nutrient and water availability; (2) Regulatory services—SOM reduces soil erosion, water run-off, and attenuation of toxic pollutants, and regulates climate change via offsetting greenhouse gas emissions; (3) Supporting services—the formation and breakdown of SOM, which can influence soil characteristics such as soil fertility and soil biodiversity; and (4) Cultural services—SOM influences the soil to retain diverse cultures of the past, the nature of the landscape and preserve archeological remains (Banwart et al., 2014a,b).

1.6 SOIL ORGANIC CARBON AND PROVISIONING SERVICES

1.6.1 PROVISION OF FOOD, FIBER, AND TIMBER

Fertile soils and sustainable practices in managed agro-ecosystems generally maintain high levels of crop, pasture, and animal production to ensure sufficient supply of food, fiber, timber, and

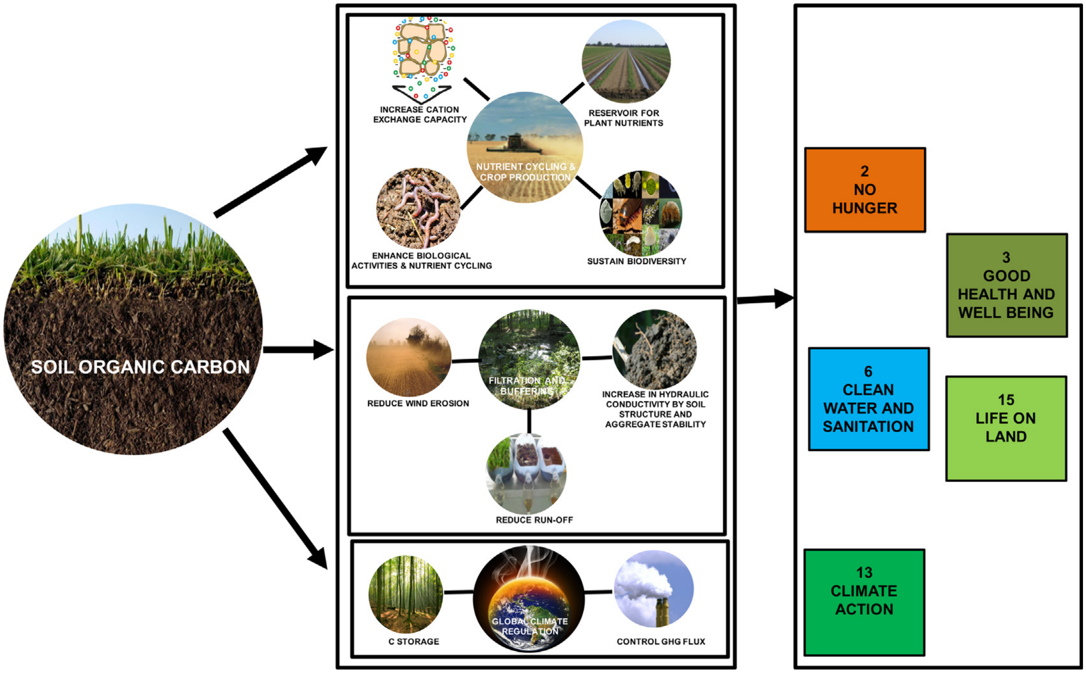

FIGURE 1.3

Soil organic carbon provides multiple functions and contributes significantly to multiple ecosystem services and is critical for the delivery of the sustainable development goals.

woodchips, thus meeting the needs of the growing human population through supporting these provisioning services (Banwart et al., 2014a,b). At the same time, fertile soils support the growth of native vegetation (forests, woodland, and grasslands) and thus contribute to the ecosystem services that native vegetation provides, including the provision of food for humans, feed for livestock, and other resources (firewood, building timbers, paper products, etc.). These managed and natural systems provide a range of other ecosystem services, including regulating and supporting services for a range of key provisioning services, while also playing a vital role in the provision of fresh water and medicines (FAO, 2017). Maximizing provisioning services from managed and native systems would result in tradeoffs with other ecosystem services they provide, but ecologically sustainable management of native vegetation and improved agricultural practices may substantially benefit supporting services and alleviate tradeoffs among the ecosystem services (Power, 2010; Smith et al., 2015).

1.6.2 PROVISION OF CLEAN WATER

Soil organic C plays an important role in water filtration and purification and soil water holding capacity by improving soil structural stability and microbial activity. Most studies show a positive relationship between SOC and water holding capacity. For example, several studies have demonstrated an increase in water content with increasing SOC content wherein an increase of 1% SOM can add 1.5% additional moisture by volume at field conditions (Haynes and Naidu, 1998; Wolf and Snyder, 2003). Soils with high levels of SOC confer resilience and promote stress resistance against drought compared to soils with low levels of SOC (Yuste et al., 2011). Porosity and connectivity of pores are two critical components of water retaining capacity of soils. SOM improves the physical conditions of soil by enhancing organo-mineral interactions and soil structure development thus providing greater pore space for water and air holding (Srinivasarao et al., 2015). Increasing the water holding capacity is essential during low rainfall periods and drought, as soil retains moisture and also slowly releases water for plant uptake (Jung et al., 2007). The water stored in soil serves as the source for 90% of the world's agricultural production and represents about 65% of global fresh water (Amundson et al., 2015). While plant growth and surface mulches can help protect the soil surface, a stable, well-aggregated soil structure that resists surface sealing and facilitates water infiltration during intense rainfall events will decrease the potential for downstream flooding. Soil chemical properties and microbial activity, on other hand, play important roles in removing contaminants from the water to minimize the pollution of ground and surface water.

1.7 REGULATING SERVICES

1.7.1 CLIMATE REGULATION

Soils represent a massive stock of C and act both as a buffer against atmospheric CO_2 increase and as a potential sink for additional C depending on the balance between photosynthesis, the respiration of decomposer organisms and stabilization of C in soils (Dungait et al., 2012). The soil C storage at 3 m depth is 3.3 times the size of atmospheric pool (760 Gt) and 4.5 times the size of the biotic pools (560 Gt) (Lal, 2004; Trivedi et al., 2013). Further, soil C sequestration can meaningfully contribute to a portfolio of mitigation approaches and potentially offset a significant fraction of diffuse CO_2 emissions for which direct capture is not yet feasible (King, 2011). In particular, it has been estimated that through judicious management, the world agricultural and degraded soils could sequester equivalent to 5%–15% of global fossil fuel emissions (Lal, 2004). While these rates will offset only a fraction of emissions from fossil fuels, results from integrated assessment analyses (Edmonds et al., 1999; Rosenberg et al., 1999) indicate that soil C sequestration may have an important strategic role due to its potential for early deployment and low costs options to mitigate climate change. However, the influence of climate change on the soil C storage and sink remains a major area of uncertainty considering the feedback from various tightly linked biotic and abiotic factors on soil C cycles (see Chapter 8: Impact of Global Changes on Soil C Storage—Possible Mechanisms and Modeling Approaches for details). Various studies have suggested that conversion of native land for agriculture practices have resulted in 40%–60% reduction in SOC from preclearing levels that has resulted in the emission of approximately 150 Gt of CO_2 into the atmosphere (Guo and Gifford, 2002). The estimates of SOC loss varied, however, depending on factors such as annual precipitation, plant species, and the length of study periods (Trivedi et al., 2016a). It has been suggested that recapturing even a small fraction of these legacy emissions through improved and innovative land management practices that help building SOC in agro-ecosystems will not only lead to lowering the rate of GHG emissions, but also increase various ecosystem services including primary productivity and soil functionality.

1.7.2 REGULATION OF SOIL STRUCTURE

Soil organic C binds mineral particles to form aggregates (Oades, 1993), whose distribution and stability influence the soil's physical properties, including pore size distribution, bulk density, soil strength, and soil erodibility (Tatarko, 2001; Chapter 3: Microbial Modulators and Mechanisms of Soil Carbon Storage). Loss of organic matter affects soil structure and aggregate formation, with negative impacts on biological diversity, soil fertility, crop production potential, erosion control, water retention, matter exchange between soil, atmosphere, groundwater, and the filtering, buffering, and transforming capacity of terrestrial ecosystems (Huber et al., 2001; Kirchmann and Andersson, 2001). Soil management practices that improve formation of soil aggregates through an increase in SOC have demonstrated minimizing soil and nutrient losses through erosion mitigation and eutrophication of surface waters (Srinivasarao et al., 2015). The success of these soil management systems, however, relies strongly on site-specific characteristics, farmers' awareness and knowledge, and often on weather events.

1.8 SUPPORTING SERVICES

These services underpin the delivery of all other services and benefits that are obtained by the natural environment, including biomass production, soil formation, nutrient cycling, and provision of habitat for biodiversity. Therefore, understanding their responses to key drivers, such as climate change, land use change, and nutrient enrichment, is vital for the sustainable management of global land and water resources. SOM is a key attribute with influence on soil's capacity to sustain and provide supporting services. Thus, SOC is not only a component of soil capital, but a relative change in SOC is potentially a practical indicator of changes in flows of supporting ecosystem services and associated soil natural capital. Relative changes in SOC concentrations can be correlated with changes in soil biodiversity, which further impacts on other provisional and supporting ecosystem services. For example, a decline in SOC concentrations has been shown to have a negative effect on the supporting services which in turn reduce both maximum yield and fertilizer use efficiency in agro-ecosystems (Brady et al., 2015). Supporting services are all strongly interrelated and, in many cases, underpinned by a vast array of physical, chemical, and biological interactions. Our understanding of the connectivity among and within different variables (namely, flow of nutrients, energy, and information) and the relative contribution of interconnected variables in driving supporting services is generally limited.

1.8.1 NUTRIENT CYCLING

1.8.1.1 Reservoir of nutrients

SOM is an important source of nutrients for plants. With the exception of fertilizers, SOM provides the largest pool of macronutrients with >95% of N and S and 20%−75% of P found in SOM (Duxbury et al., 1989; Baldock and Nelson, 2000). Heterotrophic organisms mineralize SOM wherein some soil nutrients are used in the synthesis of new biomass, wherein a portion is immobilized and another portion is released as plant-available forms. In relation to N supply from plant residues, 1% SOC is considered as the threshold value below which an effective N supply is reduced (Loveland and Webb, 2003). Soil aggregates may provide an important transient storage capacity for macronutrients and the size of aggregate classes can influence nutrient availability. Studies have shown greater mineralization of both C and N in macro-aggregate associated SOM compared with microaggregates (Nimmo and Perkins, 2002; Trivedi et al., 2015, 2017). Land management practices can affect the nutrient status and release from SOM. For example, conservational agricultural practices that increase the SOM content may reduce the availability of nutrients to crops with a gradual accumulation of nutrients in SOM over time (Duxbury et al., 1989).

There has been an ongoing debate on "using" SOM to release nutrients for plant growth in shorter terms (Janzen, 2006) versus "saving" SOM to provide long-term benefits with respect to C sequestration and enhancing long-term soil quality (Lal, 2004). These two processes may occur in distinct components of SOM wherein the relatively labile fast-cycling POM serves as a source of nutrients while the recalcitrant slow cycling mineral associated C serves as a long-term storehouse of SOC (Wood et al., 2016; Lehmann and Kleber, 2015; Trivedi et al., 2017). Different sized aggregates show an uneven distribution of labile *versus* recalcitrant C wherein the amount of labile C decreased from macro- to microaggregates and vice versa (Trivedi et al., 2015, 2017). The current paradigm suggests that accumulation of different SOM fractions is controlled by different mechanisms, potentially leading to different relationships with management outcomes (Janzen, 2006; Schmidt et al., 2011; Wood et al., 2016; Trivedi et al., 2017). Thus, understanding the controls on each of these pools and quantifying their impacts on different services provided by SOC will help in designing effective soil management practices for sustainable agriculture.

1.8.1.2 Cation exchange capacity

A high soil CEC is regarded as favorable as it contributes to the capacity of soils to retain plant nutrient cations, thus reducing the potential for leaching in soil. The contribution of SOM/SOC to CEC varies between 25% and 90% (Stevenson, 1994) and there is generally a very good correlation between SOC and CEC (McGrath et al., 1988). Humus, being highly negatively charged, has the potential to hold enormous cations, which enable soils to retain plant-available nutrients for a longer period of time such as via cation bridging. Soils with reduced CEC lead to low pH resulting in soil acidification, which further lowers crop productivity (Cork et al., 2012). Soil organic C influences soil pH and buffering capacity (Cayley et al., 2002). Soil organic C has a buffering capacity of over 300 times than that of clay minerals such as illite and kaolinite. As a result, soils with high SOC are less susceptible to acidification compared to highly weathered soils that are low in SOC.

1.8.2 PROVISION OF GENETIC RESOURCES

Soil biodiversity (including organisms such as bacteria, fungi, protozoa, insects, worms, other invertebrates, and mammals), supported by SOM pools, enhances the metabolic capacity of soils and plays a crucial role in soil health and ecosystem functioning. The highly diverse underground communities are immersed in a framework of networks that: (1) Determine the net flux of C between the atmosphere and soils, and (2) Cycle SOM thus influencing nutrient availability. The revised World Soil Charter states that soils are a key reservoir of global biodiversity which ranged from microorganisms to flora and fauna. The biodiversity has a fundamental role in supporting soil functions and, therefore, ecosystem goods and services associated with soils. It is thus necessary to maintain soil biodiversity to safeguard these functions.

The quality and quantity of SOC/SOM directly influences soil biodiversity and activities, as it is the main source of energy for their survival and growth. Indirectly, it regulates the soil biodiversity by influencing the habitat properties such as soil aggregates, pore size, and connectivity. The quality and quality of SOM/SOC determines the abundance, diversity, and activities of soil communities, but these are circular interactions, where soil biodiversity also determines the quality and quantity of SOC, and there are multiple interactions which influence the rate and aspects of C cycling and ecosystem functions (Delgado-Baquerizo et al., 2016a,b; Trivedi et al., 2016b; Delgado-Baquerizo et al., 2017a,b). Recent studies provide evidence that soil diversity and functional community diversity are strongly linked to enzymes that degrade SOC, suggesting microbial community regulation of SOC storage (Trivedi et al., 2016a). Soil microbial respiration accounts for 50% ($\sim$60 billion tonnes year^{-1}) of the net terrestrial flux while microbes are the main regulators of rate of decomposition (Karhu et al., 2014). However, soil fauna also plays a significant role by manipulating and controlling microbial communities even though they have minor direct contribution via litter fragmentation, partial digestion of litters, and promoting direct contacts between litter and microbial communities (Orgiazzi et al., 2016).

There is increasing evidence that SOC is one of the main drivers of microbial diversity, community structure, and abundance at global and regional scales (Delgado-Baquerizo et al., 2016a; Louis et al., 2016). Studies also suggest that SOC quality and soil aggregation create distinct niches for different microbial communities. For example, the SOC associated with macroaggregates (relatively labile SOC) promotes microbial diversity and community structure which are distinct to microbial communities associated with SOC of microaggregates (Trivedi et al., 2015, 2017; Rillig et al., 2017). Higher diversity provides a higher reservoir of gene pool for harnessing their functional capabilities for the betterment of the ecosystem and human societies. Loss of belowground diversity linked to soil C loss has significant consequences, hence understanding relationships between soil biodiversity and C cycling is critical for projecting how the loss of diversity under continued environmental alteration by humans will impact global C cycling processes (De Graaff et al., 2015) and other ecosystem functions (Delgado-Baquerizo et al., 2016a,b; 2017a). Current research indicates that soil biodiversity can be maintained and partially restored if managed sustainably. Promoting the ecological complexity and robustness of soil biodiversity through improved management practices represents an underutilized resource with the ability to ultimately improve human health (Nielsen et al., 2015). Other than being drivers of ecosystem functions, soil organisms have also been a source of many industrial products including medicines, genes for genetically modified crops, and chemicals/enzymes for food and chemical industries worth trillion of dollars (Singh, 2010). Going forward, harnessing natural resources (microbes, fauna, flora) together with SOM, is considered as the most effective approach for sustainable increase in farm productivity, mitigating climate change, and restoring degraded environments. Further evidence of the relationships between soil biodiversity and functioning with regard to SOC dynamics and primary productivity at farm scales can help in bridging the knowledge gaps in the biotic regulation of SOC turnover and plant productivity. This will represent a major advancement, not only in ecology, but also in agriculture in the context of global climate change and food security (Lemanceau et al., 2015).

1.9 CULTURAL SERVICES

1.9.1 HUMAN AND PLANETARY HERITAGE

Soil is one of the main sources of information on the prehistoric culture of humankind. For example, archeological remains preserved in water-saturated peatlands for about 2500 years have provided important information on the origin of human civilization. Similarly, ancient cities sat beneath the soil for thousands of years and provided preserved relics of ancient civilizations (Banwart et al., 2014a,b). Some portions of SOC survive millennia and therefore can provide critical information on human and planetary heritage. Stable isotope composition of SOC can provide evidence for pedogenic and climatic conditions for past millennia (Kovda et al., 2016). Similarly, measurements of ^{14}C in SOC have provided evidence on soil processes since the first nuclear explosion in 1950s (Lal, 2007). In addition, land use as a sense-of-place has been embodied within the cultural and spiritual beliefs of indigenous peoples throughout the world.

1.9.2 RECREATIONAL AND ESTHETIC EXPERIENCES

Soils provide esthetic and recreational values through landscape, particularly in Globally Important Agricultural Heritage Systems (Altieri and Toledo, 2011). They have also been used as an esthetic approach to raise soil awareness in contemporary art (Feller et al., 2015). Because SOM provides regulating services associated with water retention and purification, it is key for meeting recreational and esthetic values provided by water bodies that include swimming, water sports, and fishing (van den Belt and Blake, 2014). Certain soil types are more valuable than others in providing recreational benefits to the communities. Retisols that typically carry a temperate needle-leaf evergreen forest/woodland on often steeply sloping land are highly valued for forestry, recreation, and watershed protection. Gardening is one of the most important recreational activities across the globe (Comerford et al., 2013) and is recognized as a viable treatment to cure a wide range of mental and emotional conditions (Rice and Remy, 1998). Patients suffering from physical trauma and surgery recover rapidly just by viewing gardens while "healing gardens" have become an important component of hospital designs (Cooper Marcus and Barnes, 1999).

1.10 STATUS, THREAT, AND OPPORTUNITY

Status: Many estimates of global SOC stocks have been published during the past 70 years to support the calculation of potential CO_2 emissions from the soils under land use and land cover change and/or climate change scenarios (Don et al., 2011). More recent studies have reported a global soil estimate of roughly 1417−1500 Gt of C stored in the first meter of soil and about 716 Gt organic C in the top 30 cm (Köchy et al., 2015). There are fewer estimates of global SOC stocks below 1 m. Global SOC stocks to a depth of 3 m are estimated at 2344−3000 Gt (Guo and Gifford, 2002; Jobbágy and Jackson, 2000). Large variations in the SOC stock estimates may be attributed to various factors including the lack of large-scale dataset, analysis methods applied, extrapolation, and the uncertainties concerning certain soil types such as Arctic and peatlands in South Asia.

Both SOC stocks and their contributions to total C stock vary with latitude and among climatic regions (Fig. 1.4; more details in Chapter 5: Climate, Geography and Soil Abiotic Properties as Modulators of Soil C Storage). Most of the SOC is stored at northern latitudes, particularly in the "Boreal Moist" (356.7 Pg C) and "Cool Temperature Moist" regions (201.3 Pg C). With 117.6 and 88.2 Mg C ha^{-1}, these climatic regions also have the highest SOC densities. Regions near the equator in wet and moist tropical forests (including Amazonia's rainforest, the Congo basin and South-Eastern Asia) also known as the "green lungs" of the planet, store vast amount of C either in vegetation or soils (Deng et al., 2016). In fact, for the terrestrial pool of SOC, biomass is the most important pool only in "Tropical wet" and "Tropical Moist" climate regions while soil stores more SOC than the biomass in all the other climatic regions (Scharlemann et al., 2014; Fig. 1.5). As a general propensity, soil dominates the terrestrial C pool in cooler climates while vegetation dominates terrestrial C pools in tropical regions. A large fraction of boreal forest and tundra regions has additional C stored beneath the permafrost layer. In response to climate change scenarios, thawing of permafrost could release large amounts of C as CO_2, or in swamps and bogs, as CH_4, which could further amplify climate change (Schuur and Abbott, 2011). Within different vegetation classes, broadleaf forests (509.4 Gt C) represent the largest stock for terrestrial SOC (Lefèvre et al., 2017). These forest types contain approximately one quarter of all terrestrial SOC in either soils or the biomass. All the vegetation classes except for "Forest/Cropland Mosaic" store more C in soil compared to biomass. Historic trends in the fluctuations of SOC have shown that conversion of natural to agro-ecosystems in the past has led to a decline in the SOC stocks. However, the magnitude of the historic loss differs among soils, climate, and the adopted management practices. For example, a 2017 study indicated that climate legacies help to predict global soil C stocks in natural

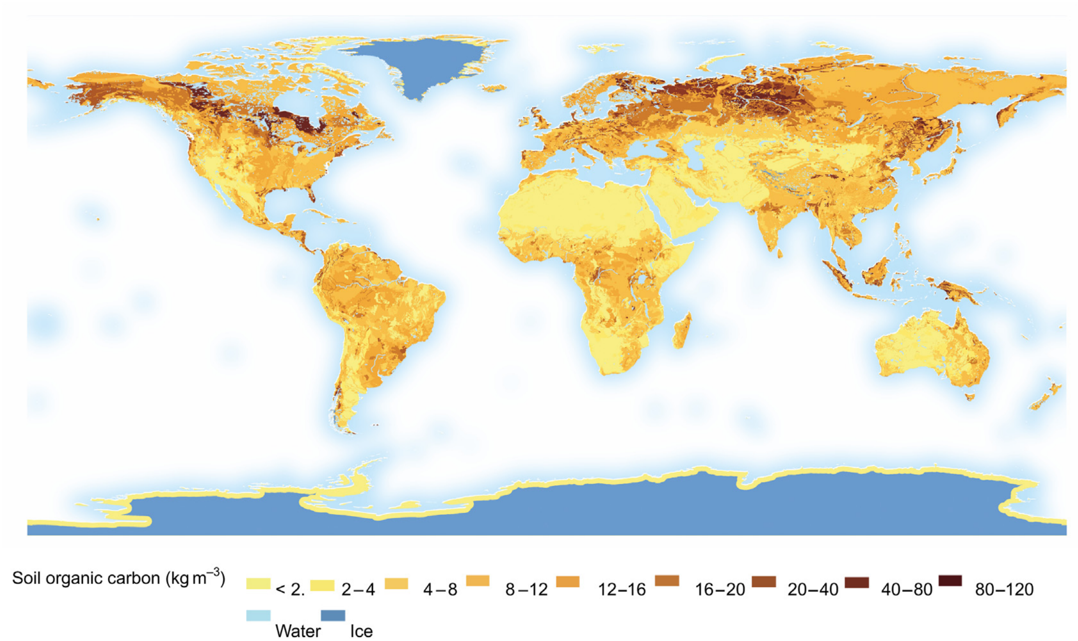

FIGURE 1.4

Global map of soil organic carbon based on FAO-UNESCO. The map shows global distribution of soil organic carbon to a depth of one meter.

Reproduced with permission from Global Biodiversity atlas.

terrestrial ecosystems, whereas SOC in arable land is strongly correlated with current climate conditions (Delgado-Baquerizo et al., 2017a,b). These findings emphasize the importance of considering how climate legacies influence soil C content, thus allowing improvements in quantitative predictions of global C stocks under different climatic scenarios.

Different soils have different capacity to store SOC. At the global level, the SOC is concentrated in five major soil orders: histosols (357 Gt), inceptisols (352 Gt), entisols (148 Gt), alfisols (127 Gt), and oxisols (119 Gt) (Eswaran et al., 1993). SOM tends to increase as the clay content increases. Under similar climate conditions, the organic matter content in fine textured (clayey) soils is two to four times that of coarse textured (sandy) soils (Prasad and Power, 1997). This increase depends on two mechanisms. First, bonds on the surface of clay particles with organic matter are less vulnerable to the decomposition process. Second, soils with higher clay content increase the potential for aggregate formation.

Threat: Global stocks of SOC are under threat from multiple activities including dramatic changes in land use and climate change, with consequences for the loss of ecosystem services, increase in GHG emissions, and acceleration of global warming (Lal, 2010a,b). The current rate of SOC loss due to land use change (deforestation) and related land-use activities (tillage, biomass burning, residue removal, excessive fertilizers, erosion, and drainage of peatlands) is between 0.7

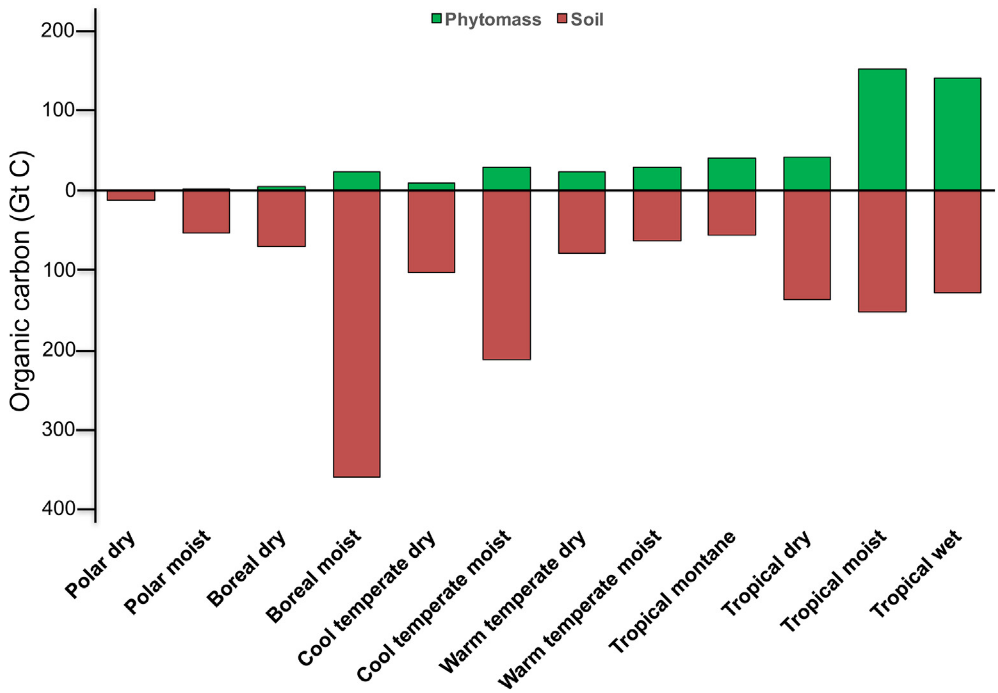

FIGURE 1.5

Distribution of terrestrial (soil and vegetation) organic carbon by IPCC climate region in soil.

The figure was adapted from Scharlemann, J.P., Tanner, E.V., Hiederer, R. and Kapos, V., 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag. 5(1), 81–91 with permission which was based on data from Hiederer, R., Köchy, M., 2011. Global Soil Organic Carbon Estimates and the Harmonized World Soil Database. EUR 25225 EN. Publications Office of the EU, Luxembourg. (Hiederer and Köchy, 2011) and Ruesch, A., Gibbs, H., 2008. New Global Biomass Carbon Map for the Year 2000 Based on IPCC Tier-1 Methodology. Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory, Oak Ridge, TN (Ruesch and Gibbs, 2008).

and 2.1 Gt C year^{-1}. Conversion of natural vegetation for agriculture land-use systems has led to a decrease of 60% and 75% of SOC stocks in temperate and tropical regions, respectively (FAO and ITPS, 2015). Today, 33% of land is moderately to highly degraded due to erosion, salinization, compaction, acidification, and chemical pollution of soils. The Intergovernmental Technical Panel on Soils (ITPS) concluded on the basis of the Seven Regional Assessments completed for the 2015 state of the Worlds' Soil resource that currently the SOC status in fair only in North America and poor in other regions, including Asia, Europe and Eurasia, Latin America, and the Caribbean Islands, Southwest Pacific, and Southwest pacific, Africa South of the Sahara, Near East and North Africa (FAO and ITPS, 2015). Soil erosion is the major land degradation process that accounts for up to 1.2 Gt of C emitted into the atmosphere each year. The annual soil losses in Africa, South America, and Asia are estimated at 39–74 Gt, which corresponds to C emissions of 0.16–0.44 Gt per year. Further, loss of productive soils severely damage food production and food security, amplify food-price volatility, and potentially plunge millions of people into hunger and poverty. But, the report also provides some evidence that the loss of soil resources and functions can be avoided.

Global SOC stock is sensitive to multiple climate change drivers. Drier, warmer conditions are expected to coincide with greater potential for the loss of SOC and associated soil functions. It is estimated that drylands in Central Asia lost approximately 0.46 Gt of soil C during the decade of drought between 1998 and 2008, which was possibly related to protracted La Niña episodes (Li et al., 2015). Climate change is positively correlated with the increasing rates of soil respiration which is the second largest terrestrial C flux (Bond-Lamberty and Thomson, 2010). A recent study predicts that for 1°C of warming, about 30 Gt of soil C will be released into the atmosphere, or about twice as much as could be emitted annually due to human-related activities (Crowther et al., 2016). This is particularly concerning because previous climate studies predicted that the planet is likely to warm by 2°C by mid-century (Gornall et al., 2010). Warming will result in the loss of permafrost that will expose accumulated C in cold regions to much greater rates of microbial decomposition (Schuur and Abbott, 2011). Although most of the studies have predicted SOC losses in response to warming, it should be noted that there are several other biological processes—such as accelerated plant growth as a result of CO_2 increases and warming—that could dampen or enhance the effect of SOC loss feedback (Nie et al., 2015; Crowther et al., 2016). Understanding these interacting processes at a global scale is critical to better predict the effect of climate change on SOC stocks.

Opportunity: Beneficial management of SOC offers opportunities not only to avoid negative consequences, but also to enhance a wide range of soil functions and ecosystem services. The most cost-effective mitigation options include afforestation, sustainable forest management, and reducing deforestation, with large differences in their relative importance across regions. In agriculture, best cropland management options are many for supporting and enhancing soil functions, including reduced tillage, crop rotation, integrated nutrient management, adding cover crops and particularly legumes during fallow periods, incorporating perennial vegetation, optimal grazing, and soil restorations with organic amendments (Machmuller et al., 2015). Thompson et al. (2008) estimated that by using current best land management practices, terrestrial C sequestration can reach a peak rate of 0.5–0.7 Gt C year^{-1} by mid-century with contributions from agricultural soils (0.21 Gt C year^{-1}), reforestation (0.31 Gt C year^{-1}), and pasture (0.31 Gt C year^{-1}). Climate smart agriculture that includes farm biodiversity, carbon farming, farmland conservation, integrated livestock and crop systems, renewable energy, and water conservation has been proposed to reduce agriculture's contribution to climate change by soil C sequestration and offsetting greenhouse gas emissions (Chapter 7: Agricultural Management Practices and Soil Organic Carbon Storage and Chapter 9: Projecting Soil C Under Future Climate and Land-Use Scenarios (Modeling)). Land managers, farmers, and producers can abate emissions and enhance soil C sequestration using several methods, but these stakeholders must be supported by education, incentives, and better decision support tools for the most appropriate approach on case-based situations.

A more unconventional root focused intervention has been proposed to breed plants for larger, deeper root systems, hence increasing plant C inputs and soil C sinks (Lynch and Wojciechowski, 2015). Paustian et al. (2016) have estimated that a sustained increase in root C inputs might add about 1 Gt CO_2 (eq) year^{-1} or more if applied over a large portion of global cropland area. In fact, it is well recognized that perennial grasses that incorporate greater root C can maintain higher SOC stocks compared to annual crops (Conant et al., 2001). In the United States, Advanced Research Projects agency—Energy (ARPA) has initiated a new program, Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS), that aims to improve crop breeding for enhancing root traits and soil functions, allowing for greater C storage in both plants and soils. Addition of plant-derived C following biomass carbonization (biochar) can also increase soil C stocks (Singh et al., 2012, 2015). The carbonized biomass decomposes slower than fresh plant residues and can be retained in the soil over several decades or longer depending on the amendment type, soil conditions, and nutrient content (Schmidt et al., 2011; Singh et al., 2012; Singh and Cowie, 2014; Lehmann and Joseph, 2015). By considering the scenario of a 30-year start period for the adoption of biomass carbonization to the level of 1% of global NPP, Post et al. (2009) estimated that a characteristic storage time of 80 years will yield a net sequestration of 19 Gt C in the next century.

1.11 VALUE OF ECOSYSTEM SERVICES PROVIDED BY SOC

Soil organic C is an asset that provides multiple ecological and societal benefits and, therefore, demonstrating the economic values of these benefits can promote SOC storage by practitioners and land owners/managers (Pascual et al., 2014), while providing valuable information for policymakers. The different components of the value of SOC differ both conceptually and with respect to how they can be measured or manifested. There are various methods for quantifying SOC values that differ with respect to the types of values they are suitable for, or able to assess. Policies have been developed that have placed an economic value to SOC storage. Many C-valuation mechanisms are in place, and despite challenges over the past decade, the valuation of C is expanding rapidly both at local and national scales (Newell et al., 2013). A number of regulated and voluntary markets have valued C accumulation in terrestrial ecosystems including forests and grasslands, and protocols have been developed with a clear view of the economic importance of SOC storage (Kelly and Schmitz, 2016). Cost-effective SOC storage, whereby C stocks in agricultural lands are enhanced, can create a value of up to US$480 billion, while increasing food and water security (http://www.greengrowthknowledge.org/resource/value-land-prosperous-lands-and-positive-rewards-through-sustainable-land-management).

Economic valuation of SOC provides information to help assess how efficiently a particular land management can reallocate goods and services from soil to different (and often competing) uses. In the United States, Wander and Nissen (2004) found the total value of SOC to be US \$3.15 tons^{-1} C ha^{-1} year^{-1}(t^{-1} C ha^{-1} year^{-1}) from the top 30 cm, the majority being from productivity enhancement (\$2.73 t^{-1} C ha^{-1} year^{-1}) and smaller benefits from fertilizer replacement (\$0.40 t^{-1}C ha^{-1} year^{-1}) and water quality enhancement (\$0.02 t^{-1} C ha^{-1} year^{-1}). Belcher et al. (2003) estimated the value of SOC changes in the Canadian Prairies to be between a loss of \$0.03 t^{-1} C ha^{-1} year^{-1} and a gain of \$0.74 t^{-1} C ha^{-1} year^{-1}, depending on soil type, crop rotation, and soil management methods. Petersen and Hoyle (2016) estimated the marginal value of SOC (the value of a soil with more SOC, by 1 t^{-1} C ha^{-1}, than a standard soil) to be AU \$7.1–8.7 t^{-1} C ha^{-1} year^{-1}, depending on rainfall zone and crop type. Approximately 75% of this value was the estimated C sequestration, 20% was the N replacement, and 5% was the estimated productivity improvement value. These estimated benefits equated to the value of \$130−160 t^{-1} C ha^{-1} over 50 years (Petersen and Hoyle 2016). It must be noted that most of these estimates focus exclusively on the on-site benefits of SOC in production systems and do not take into account the off-site benefits, including improved surface and groundwater quality. Farmers value environmental assets differently, and may adopt practices that increase SOC due to the environmental and societal values they place on SOC (Lal, 2014).

We argue that putting an economic value of SOC that takes into consideration all the ecosystem and societal services it provides, will signal the scarcity of the resource from a social viewpoint, and also the extent to which investment in enhancing SOC should be prioritized, relative to other investments (Pascual et al., 2014). Valuation of SOC will help policymakers to determine what type of economic instruments or incentives are necessary to align privately and socially optimal soil conservation decisions. Mapping the ecosystem service values of SOC needs to account for who appropriates the different values (private vs social values), whether the values are direct or indirect, and how to best emphasize the natural insurance value of SOC (Pascual et al., 2014). Combining SOC storage with other conservational efforts (i.e., biodiversity and wildlife) may well enhance the economic arguments for increasing SOC and conservation even further. Such assessments would illustrate the immense economic importance of SOC, and enable scientists, policymakers, and stakeholders to reverse the trends of SOC degradation which is bound to impact on the sustainability and productivity of ecosystems and the future well-being of the planet. While the demonstration of the economic value of SOC is important from a policy perspective, the exact value of SOC to humankind and terrestrial life is immeasurable—given the central role of SOC.

1.12 POLICIES ON SOIL CARBON

Because SOM is a major contributor of soil health and can be built up, or lost by, the type of land management, it is recognized as one of the most relevant targets for human well-being and conservation interventions. The 2015 Status of the World Soil Resources report (FAO and ITPS, 2015) highlighted that SOC is critical in the global C balance, and national governments must set specific targets to maintain or ideally increase SOC storage. These reports emphasize that the most significant threats to soil function at the global scale are soil erosion, loss of SOC, and nutrient imbalance. The reports also point that warming-induced changes in soil temperature and moisture regimes may increase the SOM decomposition rate and intensify the risks of erosion and desertification.

The introduction of the United Nations SDGs offers a unique and welcome opportunity to direct joint activities toward ending poverty, protecting the planet, and ensuring prosperity for all. These SDGs build on the success of the Millennium Development Goals, while including new areas such as climate change, economic inequality, innovation, sustainable consumption, peace and justice, among other priorities. These goals are interconnected—often the key to success of one will involve tackling issues more commonly associated with others. Soil science plays an important role in realizing a number of SDGs focusing on food, water, climate, health, biodiversity, and sustainable land use (Fig. 1.3). As such, SOC is included in the monitoring of SDG indicator 15.3.1, under which belowground and aboveground C stocks are one of the three indicators (along with land cover and land cover change, and land productivity) to determine the proportion of land that is degraded over the total land area. Addressing the increasing trends in soil and land degradation primarily due to the loss of SOC is a critical challenge for sustainable development of agro-ecosystems since soil degradation processes can have adverse effects on nearly all the ecosystem services provided by SOC, including food security, water quality and availability, human health, and social and economic well-being of human society. Consistent increment in the SOC stocks will increase the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security, particularly in developing countries that are worst affected by desertification and land degradation.

The SDG 15.3.1 advocates the establishment of a baseline for C stocks, aboveground and belowground, with an emphasis on SOC. The Intergovernmental Panel on Climate Change (IPCC) has conceptualized guidelines for the assessment of SOC and its stock changes in the context of offsetting GHG emissions. However, despite widespread recognition of the importance of SOM, there are no reliable, quantitative targets for the amount of SOM required to achieve SDG relevant impacts, such as soil health, C sequestration, and nutrient reductions in waterways, biodiversity conservation, and sustainable land-use. The immediate challenge for soil scientists is to develop multi-disciplinary, system-level, harmonized methodologies for standardized sampling protocols, data collection and sharing, robust modeling, as well as adaptation and implementation by stakeholders. The Global Soil Partnership (GSP) and members of Food and Agriculture Organization (FAO) of the United Nations are currently working on the establishment of the Global Soil Information System to improve science-based soil management by quantifying the relationships between: SOM and crop yield, and C storage, biodiversity outcomes and nutrient retention. The Global Soil Organic Carbon (GSOC) map is proposed to be released by December 2017 which will contribute to develop SOC stocks as an indicator of land degradation (as proposed in SDG 15.3.1). Such an approach that aims to improve information on SOC stocks can constitute a unique option to reinforce the current IPCC assessment and for reporting to the United Nations Framework Convention on Climate Change (UNFCCC), the UNCCD, and SDG 15.3. These initiatives could further provide valuable information to support the IPCC sixth assessment report (AR6) and its products by contributing to the methodology report(s) to refine the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

At the 21st Climate Change Conference, the French Ministry of Agriculture launched the "4 per 1000" initiative. This initiative calls on nations to increase the C content in the top 40cm of their soils by 0.4% per year. This equates to annually removing approximately 3.5 Gt of C from the atmosphere. This initiative has been signed off by 32 nations, including Germany, France, United Kingdom, and Australia, as well as dozens of agricultural and civil society agencies. The "4 per 1000" initiative also aims to strengthen existing synergies between the three Rio Conventions—UNFCCC, UNCCD and the Convention on Biological Diversity (CBD)—and the Committee for Food Security (CFS), GSP, and SDGs. The initiative aims to reach its goals by: (1) Implementing training programs for farmers and agricultural advisors which aim to enhance organic matter in soils; (2) Contributing financially to C sequestration development projects; and (3) Developing policies that promote sustainable management of soils. In the United States, the National Science and Technology Council's Soil Science Interagency Working Group developed a framework for the federal strategic plan for soil science development. This framework identifies "climate and environmental change" as one of the three overarching "Challenge and Opportunities" categories, and recognizes the need for "terrestrial C sequestration" in soils and forests. In the United States, several states have framed and adopted policies to build adequate SOM that can sequester soil C with the primary objective to reduce overall GHG emission and increase soil health including "Healthy Soils Initiative" in California, "Carbon Sequestration Enhancement Act" in Oklahoma, "Concurrent Restoration on Carbon Sequestration on Rangelands" in Utah, and "Regenerative Soils Program legislation" in Vermont.

In spite of the fact that SOC plays a key role in soil quality and environmental health, its importance has mostly not been translated into international actions. This disconnect between the science and policy arenas at local, national, and global levels can only be resolved with an innovative framework that provides simple and clear messages to all stakeholders, equating SOC with societal priorities like growth, income, jobs, and social welfare (van Wesemael et al., 2011). The starting point should be the key cross-cutting role of SOC toward high profile topics such as food security, environmental sustainability, climate change scenarios, societal development, human well-being, and bioeconomy.

1.13 CONCLUSION

Land use change, such as conversion of native vegetation to cropping systems, and unsustainable agricultural management practices caused significant loss of SOC and land degradation over several decades. As SOC is critical for the maintenance of multiple ecosystem services related to soil health and functioning, it is considered as a strong determinant of global food and nutritional security. Improved management strategies to enhance SOC storage can support provision of essential ecosystem services while offering part of the solution to a warming climate (Box 1.2). Sustainable soil management practices that increase SOC using scientific evidence-based and local knowledge, and proven approaches and technologies, can increase nutritious food supply, provide a valuable means for climate regulation, and safeguard multiple ecosystem services. A new focus on SOC storage at all levels of governance for soil management would better enable the full potential of

BOX 1.2 TAKE HOME MESSAGE

- Soil stores more carbon (C) than vegetation and the atmosphere together
- Soil C is an important resource and provides key ecosystem services including provision of food and fiber, habitats of biodiversity, climate regulation, water filtration and purification, human heritage
- A significant portion of SOC has been lost due to land-use change and is under threat of further loss due to climate change, soil erosion, and inappropriate land management practices.
- An appropriate management based on scientific evidence can not only minimize SOC loss but can restore additional SOC and can contribute directly to address key global challenges including food security, environmental sustainability, and climate change mitigation and adaption.
- Increasing SOC storage can significantly improve our ability to achieve aims of multiple global and national policies including Sustainable Development Goals, and aims of IPCC, FAO, UNCCD.
- An effective integrated approach is needed which can consolidate current national and intergovernmental policies, in order to achieve stated goals of increment in SOC stocks.

ecosystem services to be realized. Therefore, several suggested soil conservation practices need to be implemented to increase SOC storage and reach the maximum potential of climate change mitigation and adaptation, as well as food productivity. It is also an essential step toward developing a framework for soil management, not only to avoid negative consequences of climate change, but also to enhance the wide range of available soil functions. However, financial, technical, logistic, institutional, knowledge, and resource and socio-cultural barriers along with physical factors and their interactions, all influence the global adaptation of practices and policies aimed at building and preserving SOC in terrestrial ecosystems. Despite some recognized solutions to overcome human induced barriers, global adoption rates of sustainable soil management practices remain below the level necessary to achieve SDGs. Going forward, greater specificity and accuracy, as well as improved methods are required to measure, account for, monitor and report SOC pools. We urgently require effective integration of national and global initiatives that engage all stakeholders including land managers, scientists, policy advisors, and science advocates to draft and implement policies to manage SOC to address the key challenges of food security, mitigation, and adaptation to climate change. Such initiatives will provide a transition toward a productive, resilient agriculture based on sustainable soil management and generating incomes, hence ensuring the sustainable development of land-based resources that last to meet the needs of future generations.

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