2 Soil Carbon: a Critical Natural Resource – Wide-scale Goals, Urgent Actions

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Abstract

Across the world, soil organic carbon (SOC) is decreasing due to changes in land use such as the conversion of natural systems to food or bioenergy production systems. The losses of SOC have impacted crop productivity and other ecosystem services adversely. One of the grand challenges for society is to manage soil carbon stocks to optimize the mix of five essential services – provisioning of food, water and energy; maintaining biodiversity; and regulating climate. Scientific research has helped develop an understanding of the general SOC dynamics and characteristics; the influence of soil management on SOC; and management practices that can restore SOC and reduce or stop carbon losses from terrestrial ecosystems. As the uptake of these practices has been very limited, it is necessary to identify and overcome barriers to the adoption of practices that enhance SOC. Actions should focus on multiple ecosystem services to optimize efforts and the benefits of SOC. Given that depleting SOC degrades most soil services, we suggest that in the coming decades increases in SOC will concurrently benefit all five of the essential services.

The aim of this chapter is to identify and evaluate wide-scale goals for maximizing the benefits of SOC on the five essential services, and to define the short-term steps towards achieving these goals. Stopping the losses of SOC in terrestrial ecosystems is identified as the overall priority. In moving towards the realization of multiple SOC benefits, we need to understand better the relationships between SOC and individual services. Interactions between services occur at multiple spatial scales, from farm through landscape to subnational, national and global scales. Coordinated national and international responses to SOC losses and degradation of the five essential services are needed to empower SOC actions at local levels that have benefits on the larger scales. We propose the creation of a global research programme to expand the scientific understanding of SOC and its contribution to the five essential services. This should address the challenges and uncertainties associated with the management of SOC for multiple benefits. This research programme must include a strong education and outreach component to address concerns to different communities outside academia.

Introduction

Soil organic matter (SOM) is an essential component of Earth's life support system. Soil organic carbon (SOC), which makes up half of the SOM by weight, plays a crucial role in the regulation of the global carbon cycle and its feedbacks within the Earth system

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(Trumbore, 1997; Lal, 2003). Humans rely on SOC stocks to help meet their needs for food, water, climate and biodiversity on our planet (Hooper *et al.*, 2000). Land degradation resulting in carbon losses is of great concern because it threatens our capacity to meet the demands of the world population, which is estimated to grow to over 9 billion by 2050. The resulting increased demand for food, water and energy will put an increasingly heavy pressure on land resources and the global climate.

Scientific research has given us clear and compelling evidence that SOC stocks have been reduced in many regions of the world, with these reductions often associated with agriculture and land degradation (Amundson, 2001; Sanderman and Baldock, 2010). One of the grand challenges for society is to manage soil carbon stocks to optimize the mix of five essential services – provisioning of food, water and energy; maintaining biodiversity and regulating climate (Fig. 2.1). These essential services and their interaction with SOC could be seen in an Anthropocene perspective (Richter, 2007). The global changes in SOC provide evidence that human activities are indeed having a global impact on the Earth system and on these five essential services underpinned by SOC.

For this chapter, SOM reflects the range of all organic materials found in the soil profile that influence the physical (e.g. soil bulk density, water infiltration rates), chemical (e.g. pH, nutrients) and biological (e.g. biomass, exogenous substrates) properties of soils. In this context, SOC can be increased by the addition of organic materials into the soil profile by means of different management for different purposes (Ingram and Fernandes, 2001; Swift, 2001).

Scientific research has helped develop an understanding of both the general SOC dynamics and characteristics and the influence of soil management on SOC at different temporal scales. This combined information can be used to motivate new research efforts to identify and promote best SOC management practices at local management units and to facilitate improvements at regional to global scales. Moving forward, there is a need to identify and overcome barriers to the adoption of practices that enhance SOC. Here, we argue for the necessity of an ambitious global

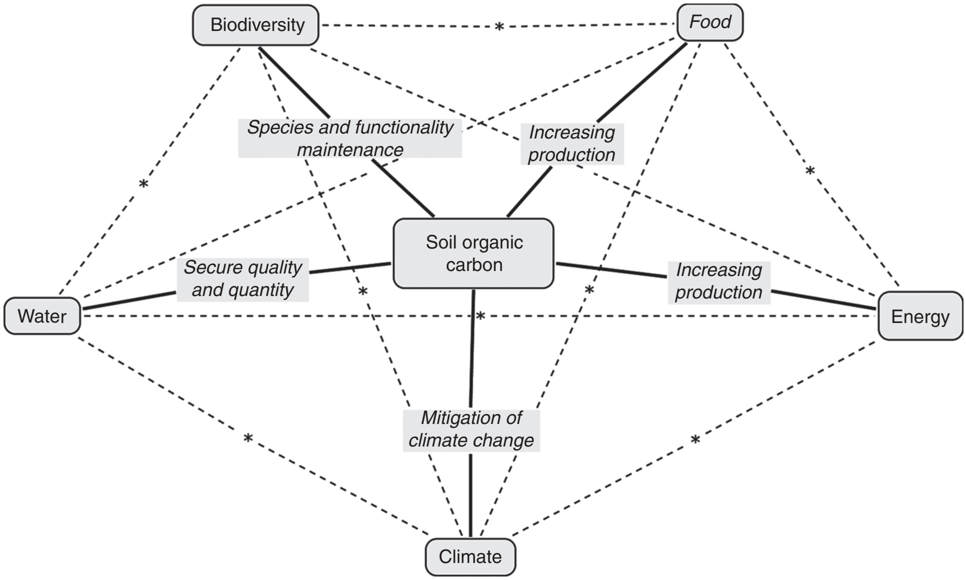

Fig. 2.1. Interactions between soil organic carbon (SOC) and the five essential services. Solid lines represent links discussed in this manuscript that refer directly to SOC. Dashed lines are interactions among essential services to show the interconnectivity.

research programme to expand the scientific understanding of SOC and its contribution to multiple environmental services, including management options towards the optimization of these services. These efforts should lead to coordinated national and international responses to SOC losses and degradation of the five essential services and empower SOC actions at local levels but be beneficial at larger scales. Thus, in moving towards the realization of multiple SOC benefits, we need to understand better the relationships between SOC and individual services to achieve long-term goals through new policy regulation and the research and development of economic incentive schemes.

The aim of this chapter is to identify wide-scale goals for maximizing the benefits of SOC on the five essential services and to define the short-term steps towards achieving these goals. First, we discuss the current knowledge on SOC and identify the feedbacks between increasing SOC and the five essential services. Second, we define the main long-term (next 25 years) challenges and uncertainties for managing SOC. We recognize that 25 years is not long term for soil carbon processes but is long term for policy and management actions towards maximizing the five essential services. Third, we outline a set of priorities and actions that will begin to move us towards optimizing the mix of benefits from these five essential services.

Wide-scale Goals and Urgent Actions

Food production

It is known that conventional agriculture reduces SOC in surface layers by up to 50% compared with natural vegetation (Jolivet *et al*., 1997; Mishra *et al*., 2010). In many parts of the world, degradation resulting from human activities has reduced the capacity of land to produce food. Underlying this degradation and declining agricultural productivity is the loss of SOC (Lefroy *et al*., 1993; Cheng *et al*., 2013). It is estimated that, on one-quarter of the global land area, soil carbon losses have caused a decline in productivity and in the ability to provide ecosystem services (Bai *et al*., 2008). In light of these facts, the goal is to increase and sustain food production to meet the demand of a growing population at both the local and global scale while increasing and sustaining SOC and the services it provides.

Soil organic C is imperative for food production because several SOC-related processes govern the availability of nutrients, water and toxins that control plant growth (Bationo *et al*., 2007). Soil carbon is the source of energy and substrate for soil microorganisms, which in turn regulate the decomposition and mineralization/immobilization processes responsible for nutrient availability (Insam, 1996; Bot and Benites, 2005). Soil organic C also improves the structure of soils by increasing the formation of soil aggregates, which enhances water infiltration and retention, thus reducing nutrient losses through leaching and runoff (Rawls *et al*., 2003; Blanco-Canqui and Lal, 2007).

It is important to acknowledge that the challenges faced in terms of increasing food production vary considerably across the globe. Increasing food production is particularly urgent in areas where current levels of food production are far below the potential levels (i.e. mainly in food-deficient regions such as sub-Sahara Africa). Food-deficient regions are characterized by low crop and livestock productivity, due mainly to soil degradation resulting from intensive land exploitation without adequate inputs of nutrients and from overgrazing (Drechsel *et al*., 2001). Low SOC affects vital soil functions such as nutrient cycling and microbial activity, both required for nutrient availability to crops. Current initiatives for fighting hunger in line with Millennium Development Goal 1, such as the African Green Revolution, need to take increasing SOC as a core component of interventions to ensure an efficient use of inputs and a sustainable increase of food production. Management practices that increase SOC and food production include fertilization, crop rotation, reduced tillage, organic matter addition, fallow, cover crops, agroforestry and improved livestock management.

Food-secure regions, predominant in developed countries, are often characterized by excess nutrient inputs in their farming systems, which can affect other ecosystem services negatively through pollution and greenhouse gas emissions (Csathó *et al.*, 2007; Vitousek *et al.*, 2009). Optimizing and sustaining current and future food production by maintaining the functionality of soils and minimizing the negative impact on other ecosystem services must be the major aim of a bold new programme of technical research and agricultural land management.

Water

Land use affects the quality and quantity of water strongly in many watersheds (Swallow *et al.*, 2009). One of the most important water pollution problems related to land use are the excess nutrients applied for agricultural production but which flow into surface and coastal waters (Ahrens *et al.*, 2008). Nitrate and phosphate contamination are well-known examples, but also pesticides enter both groundwater and surface-water bodies. Nutrients in surface waters can cause eutrophication, hypoxia, algal blooms and other infestations (such as of water hyacinth), which have been observed in coastal areas and many inland water bodies on all continents (Swallow *et al.*, 2009; Mateo-Sagasta and Burke, 2010). Water pollution has increased with the increased use of mineral fertilizers and higher concentrations of livestock (FAO, 2011). In light of these facts, the goal is to ensure the provision of sufficient quantity and quality of water needed for multiple uses by increasing SOC.

Soil organic carbon and protective vegetative cover are critical to maintaining the quality and quantity of water available for human consumption and plant production in the long term, because SOC determines soil properties that regulate in multiple ways the hydrological pathways within the soil. Soil organic carbon increases soil aggregates, which improves water infiltration and decreases the susceptibility of soil to water and wind erosion (Blanco-Canqui and Lal, 2007). The decrease in runoff and increase in infiltration contribute to recharging aquifers, and to preventing water pollution by decreasing the transport of nutrients and other contaminants to fresh waters. Soil organic carbon also improves water quality by acting as a filter of herbicide and pesticide residues and other pollutants that contaminate water reservoirs and streams (Lertpaitoonpan *et al.*, 2009; Rodriguez-Liébana *et al.*, 2013).

At the catchment scale, practices that increase SOC are required to improve water recharge (quantity) and purification (quality). In the short term, regulations at national or subnational levels, mainly in developing countries, must stimulate water erosion control measures in order to reduce the pollution of stream water and the effects of disasters such as hurricanes on the downstream population and infrastructure and to ensure the availability of potable water for human consumption (Bradshaw *et al.*, 2007; Brandimarte *et al.*, 2009). Adequate practices for increasing SOC at the catchment scale must be adopted by the farmers of the catchment area. Farmers could be grouped in farmer organizations, advised by experts from local, national and international institutions, including private organizations, and legally regulated and stimulated by the government. Practices to increase SOC that can be implemented immediately to reduce runoff and increase water infiltration include no till, cover crops, agroforestry, afforestation and others, complemented by specific technologies like terraces, contours and strip cropping (Mishra *et al.*, 2010; Powlson *et al.*, 2012). The cumulative effects of these and newer practices are hot topics for research. Land tenure policies that favour increases in SOC are needed to accompany these practices, particularly at the catchment level.

Once regulations are implemented, there is a need to monitor changes in SOC, in order to quantify its effects on the improvement of water quality and quantity. This should include the monitoring of the water table, hydrological regime and sediment loads in stream water. The results of this monitoring can be used to advise farmers, professionals and policy makers, as well as for education purposes at different levels.

Energy supply

Increasingly, plants are being grown to produce bioenergy, especially as the price of fossil fuels increases and efforts to mitigate climate change grow. The use of biomass for energy production is considered a promising way to reduce net carbon emissions and mitigate climate change (Don *et al*., 2012). The role of biomass in energy supply is expected to rise dramatically over the coming decades as cellulosic biofuel production becomes widespread. Reilly *et al*. (2012) project that an aggressive global biofuels programme could meet 40% of the world's primary energy needs by 2100. A large land area, perhaps as much as 21×10^6 km^2, would be required to produce biomass fuel crops at this large scale (Wise *et al*., 2009; Reilly *et al*., 2012). In light of these facts, the goal is to increase biomass fuel production to meet the demand for energy while increasing SOC.

As for food production, sustainable biomass fuel crop production will rely on an increase of SOC as a driver of processes regulating nutrient availability for use by these crops. However, land-use change to biomass fuel crops, particularly the conversion of native vegetation or peatlands, can result in carbon emissions from soil and vegetation in amounts that would take decades or centuries to compensate (Anderson-Teixeira *et al*., 2009; Gasparatos *et al*., 2011). The potential losses of soil carbon can counteract the benefits of fossil fuel displacement to the extent that biomass fuels from drained peatlands lead to emissions that, per unit of energy produced, exceed by far those from burning fossil fuels (Couwenberg, 2007; Couwenberg *et al*., 2010).

Maintaining or increasing biomass fuel production per unit area will require the careful management of soil carbon stocks over vast areas of the global landscape. Soil carbon management must be considered explicitly in carbon accounting efforts associated with biomass fuel production. This accounting should include both indirect effects on land use and fertilizer use and its consequences, including the release of nitrous oxide, a powerful heat-trapping gas, to the atmosphere (Melillo *et al*., 2009).

There is also evidence that some native vegetation (e.g. native grassland perennials) for biofuels could provide more usable bioenergy, larger reductions of greenhouse gas emissions and less agrichemical pollution than if the land were to be converted to producing annual bioenergy crops (Tilman *et al*., 2006; Don *et al*., 2012). Targeting degraded lands for biomass fuel production has been suggested as a potential way to reduce competition with food production and the negative effects of clearing natural vegetation and forest, particularly if perennial biomass fuel crops were grown (Kgathi *et al*., 2012). These perennial crops, if well identified, could contribute to increasing SOC on those degraded lands. There is therefore a need for full cycle analyses of biomass fuel production technologies and management regimes that take full account of the losses and gains of SOC (Davis *et al*., 2009; Gnansounou *et al*., 2009). Research should focus on monitoring the impact of land-use change for biomass fuel crop production on SOC losses and gains for proper guidelines on management for long-term benefits.

Biodiversity

Soil carbon is a primary ecosystem energy source that underpins the structure and function of terrestrial ecosystems, and thus the capacity of these ecosystems to maintain biodiversity. As illustrated in Fig. 2.2, decline of SOC comes as a second threat to soil diversity (Jeffery *et al*., 2010). Additionally, most of the other identified threats such as soil compaction and soil erosion are related to SOC losses and can be counteracted by an increase of SOC. Restoration projects around the world demonstrate that increasing SOC in degraded soils enhances not only biodiversity per se but also a range of ecosystem goods and services that can

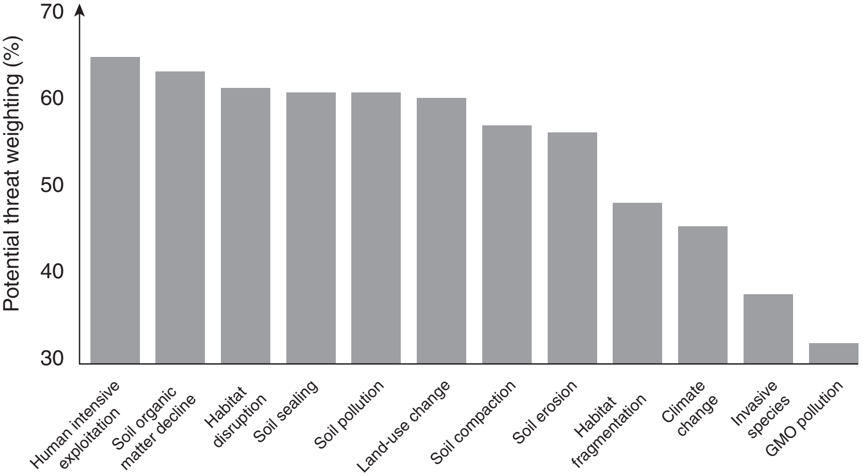

Fig. 2.2. Relative importance of possible threats to soil biodiversity in Europe as estimated by 20 soil biodiversity experts. (From Jeffery *et al*., 2010.)

benefit local people and wider communities (George *et al*., 2012). The goal here is to maintain or enhance the biodiversity of ecosystems by increasing SOC.

To date, conservation efforts to halt ongoing losses of global biodiversity have largely ignored critical interactions between the above- and belowground components of biodiversity. In part, this reflects a historical lack of information on the detailed composition and biogeography of soil communities. The application of molecular methods in large-scale surveys has begun to address this knowledge gap (Coleman and Whitman, 2005). The soil is estimated to be the largest terrestrial reserve of biodiversity (Fitter *et al*., 2005), with over one-quarter of the species on Earth living in the soil (Jeffery *et al*., 2010). The soil biota make up a complex food web consisting of microorganisms (e.g. bacteria, fungi, archaea, protozoa) through invertebrates (from nematodes to earthworms and termites) to mammals and reptiles (e.g. moles, snakes).

Soil biodiversity is important to soil quality since it has critical functional roles in the cycling of nutrients, organic matter and water, and in regulating soil structure, greenhouse gas fluxes, pest control and the degradation of pollutants. It is the presence of functional groups rather than taxonomic richness that appears to be important in soil C dynamics (Nielsen *et al*., 2011). Some of the main functional groups include litter fragmenters, decomposers of complex organic compounds, nitrifiers/denitrifiers, methanogens/methanotrophs and ecosystem engineers. Although we know these groups exist and we are rapidly gaining understanding about their roles in above- and belowground processes (Cornelissen *et al*., 2001; van der Heijden *et al*., 2008; Strickland *et al*., 2009), we still lack the ability to predict how, when and where these functional groups determine the capacity of soils to capture and store carbon and exchange greenhouse gases (Hunt and Wall, 2002).

This soil system derives its primary energy from carbon substrates obtained from root exudates, direct photosynthesis and the decomposition of organic matter from litter and plant roots. Thus, the quantity and quality of soil carbon is a key factor in determining the structure and activity of the soil community, and vice versa (Schulze, 2006). Changes in agricultural practices for food, livestock or bioenergy production affect SOC and disrupt both the below- and aboveground biodiversity. Practices to increase or maintain biodiversity include the protection of natural resources, halting land-use changes that affect natural vegetation and the restoration of degraded lands, all of which result in maintaining or increasing SOC.

Climate

Soils play a major role in the global carbon cycle, the dynamics of which have a large effect on Earth's climate system. Today, the top 1 m of soil worldwide contains about twice as much carbon in organic forms as does the atmosphere, and three times as much as does the vegetation (Batjes, 1996). Over the past three centuries, land clearing and land management for agriculture have resulted in the acceleration of soil organic matter decay and the transfer of more than 100 Pg carbon from the soil to the atmosphere as carbon dioxide (CO_2) (Sabine *et al*., 2004). In light of these facts, the goal is to mitigate climate change by practices towards ecosystem-level carbon sequestration including increasing SOC.

The extraction of peat and its use as fuel, litter or a soil improver has also resulted in substantial transfers of CO_2 (>20 Pg C) to the atmosphere over the same period (Gasparatos *et al*., 2011; Leifeld *et al*., 2011). Once in the atmosphere, CO_2 has a long half-life and it functions as a powerful heat-trapping gas that is the primary cause of the global temperature increases (IPCC, 2007). These temperature increases, in turn, accelerate SOC decay and create a self-reinforcing feedback, with warming begetting further warming (Heimann and Reichstein, 2008).

Practices that increase SOC, such as mulching and reduced tillage, increase and retain soil moisture, providing resilience to in-season rain shortages (dry spells), which are expected to occur more often in some regions as a consequence of climate change. The management of global soil carbon stocks with best practices has the potential to increase the magnitude of the SOC pool over decadal timescales to help mitigate climate change and climate variability. Two major soil science and management challenges are to: (i) minimize further losses of SOC to the atmosphere; and (ii) increase the soil carbon stocks. These two goals apply to the problem at local (catchment) and global scales, and in the short term as well as the longer term.

Interactions and Trade-offs Between Services

As illustrated above, there are many wide-scale goals and short- and long-term actions that must be implemented to meet growing human demands for food, water, energy, climate change mitigation and biodiversity in the coming decades at local and global scales. Soil organic carbon is central to these essential services and could be an important determinant of maintenance, buffering and enhancement of the supply of many ecosystem goods and other services under changing socio-economic and environmental conditions, as implied by the interactions in Fig. 2.1. Soil organic carbon, as a key component in ecosystem functioning, provides a useful mechanism to address jointly the threats to various ecosystem services. A focus on SOC enables us to set out the interactions between individual services and to assess appropriate synergies associated with actions to enhance SOC from local to global scales.

Actions affecting SOC long-term goals will inevitably have interactions and feedbacks. For example, as previously discussed, one interaction is between SOC and climate. In this case, management that induces SOC losses contributes to increasing greenhouse gas concentrations in the atmosphere, which in turn will increase air temperature and create a feedback by accelerating SOC decomposition and further losses (Heimann and Reichstein, 2008). Actions focusing on increasing the provision of one ecosystem service individually often impact various other ecosystems services negatively. We must learn from the past, where a focus on single services has led to significant reductions in the supply of other services (Tilman *et al*., 2006; Don *et al*., 2012). Typical examples are the focus on agriculture intensification for food production, which has led to water pollution and losses of biodiversity due to excess nutrients and pesticides

(Chappell and LaValle, 2011), and the clearance of native vegetation or drainage of peatlands for biomass fuel production, which also led to losses of biodiversity, water quality and quantity and contributed to climate changes through significant release of CO_2 to the atmosphere (Bessou *et al.*, 2011). Focusing land management towards a range of benefits rather than one single benefit (as is often done) is a way forward in minimizing trade-offs and maximizing synergies. It is also proposed that losses in SOC have increased the vulnerability of these services to climate change (Reilly and Willenbockel, 2010; Don *et al.*, 2012). Thus, restoring, increasing or protecting SOC could play a major role in buffering ecosystem goods and services in the future.

One view of interactions is that each essential service has an optimal operational range of SOC (Fig. 2.3). For example, while food production can, and continues to, operate at relatively low levels of SOC, there is a general hierarchy with other services requiring higher levels of SOC to be maintained effectively and for people to reap the benefits. The window for sustainable livelihoods is defined as the optimum range of C stocks that are adequate to supply all essential services. Currently, we are operating at SOC levels far below these windows, as demonstrated by global losses of biodiversity and problems with water quality and quantity (Powlson *et al.*, 2011). The boundaries to these operational limits will vary at the local scale but ultimately are tied by the global potential to store SOC. As the current stock of SOC is below the optimal stock from a societal perspective (Fig. 2.3), managing soils for multiple services implies working towards levels of SOC that will allow all services to be delivered adequately.

Interactions between services occur at multiple spatial scales, from local (e.g. farm) through landscape (e.g. catchment) to subnational, national and global scales. The inducement of most interactions takes place at farm and catchment scales, where

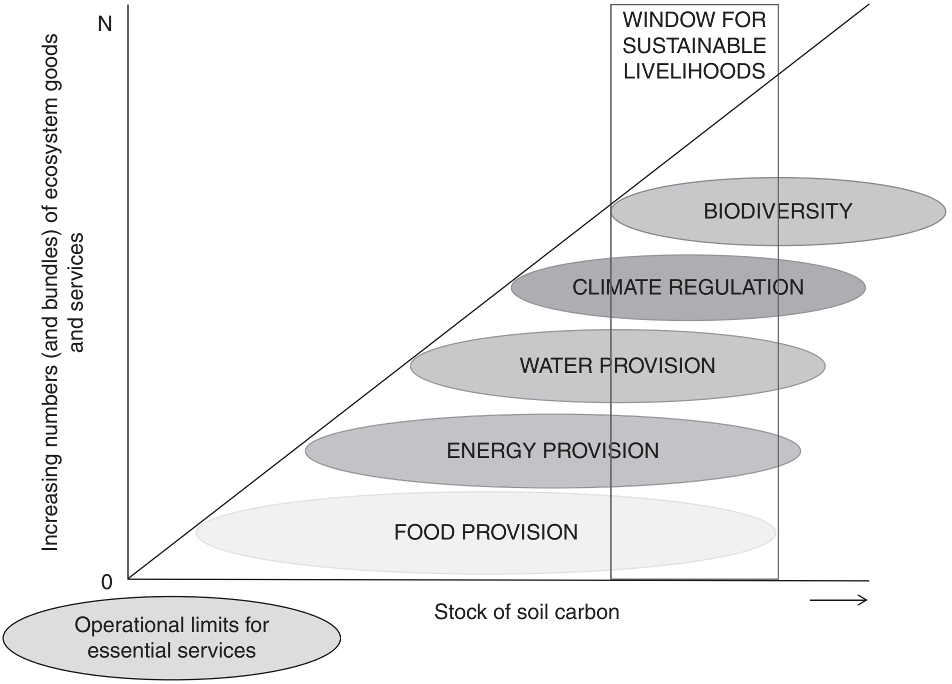

Fig. 2.3. Conceptual representation of operational ranges of essential ecosystem services in relation to SOC stocks.

people can implement management. The implications of the local management of SOC and its interactions with environmental services can have broader significance. Nowadays, given the degraded status of SOC in most managed soils and the ongoing threats to soils rich in carbon (e.g. peatlands, tropical forests), there are clear and immediate synergies between services in terms of SOC management. For example, at the farm level in low-carbon agricultural soils, there could be far-reaching co-benefits such as increased crop productivity, reduced runoff for water protection, enhanced soil biological functions and carbon sequestration. Therefore, increasing SOC could include landscape-derived benefits from water quality and quantity improvements and benefits from maintaining biodiversity by restoring soils and habitats. At the global level, improved farm- and catchment-level management to increase or maintain SOC could translate into a mitigation action for climate. However, none of the positive roles of increasing SOC for environmental services would be understood without scientific research. Therefore, a synergy must exist between academic institutions, research programmes and local communities to create public awareness and to communicate relevant findings quickly.

Uncertainties and Challenges

Across the world, there is evidence that managed soils have decreased their SOC due to changes in land use such as the conversion of natural systems to food or biofuel production systems (Leifeld *et al.*, 2011; Powlson *et al.*, 2011). The losses of SOC have adversely impacted crop productivity and other ecosystem services such as water resources, biodiversity, bioenergy and climate regulation (Bai *et al.*, 2008). Much is known about management practices that can restore the organic matter contents of soils and can reduce or stop carbon losses from terrestrial ecosystems. In many regions and cropping systems, relatively small changes in land management practices can have relatively large impacts on SOC and its derived benefits. However, the adoption of these management practices has been very limited. There is an urgent need for identifying and overcoming the barriers to the adoption of practices that enhance SOC through appropriate policies, investment and land-use planning at various scales. Furthermore, tools are needed to enhance the measurement and analysis of the costs and benefits/valuation of various practices and farming systems on the range of ecosystem services at various temporal and spatial scales, including the economic, social and environmental benefits of increasing SOC.

Given that most soils and services can benefit from reversing their depleted state of SOC, we suggest that in the coming few decades increases in SOC will concurrently improve the five essential services (Fig. 2.1). However, the potential of soils to increase SOC is dependent on time and is constrained by different factors (Fig. 2.4). It is known that under given climatic, substrate, relief and hydrologic conditions there will

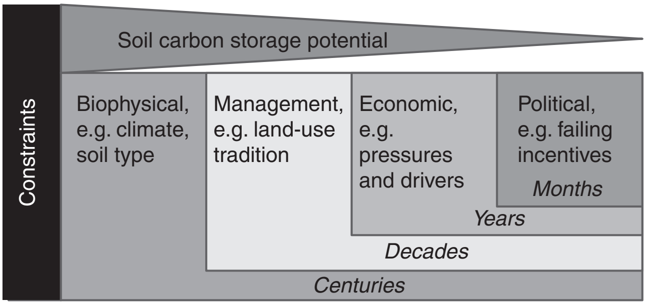

Fig. 2.4. Main constraints to soil carbon accumulation and the time frames over which they may be addressed.

be biophysical limits to how much carbon a soil can store naturally. However, the knowledge on a soil's inherent capacity to sequester carbon is absent, as natural reference soils are missing as a result of intensive land use. The biophysical limits are further constrained by land-use routines, which often have a strong historical/traditional bearing and are slow to change.

Economic drivers, in contrast, may change the cultivated crop or the land-use type (e.g. forest to grassland) rapidly, with possibly grave consequences for the soil carbon balance. Examples of the latter are changing market demands for food, fodder and energy crops. Changes in policies with implication for land use from one cultivation period to the next occur quickly and can lead to rapid and severe losses of soil carbon, as illustrated by governmental biofuel and bioenergy subsidies that stimulate the ploughing of grassland for maize cultivation or the drainage of peatlands. In view of the various constraints, a research management plan must be implemented along with management actions to monitor and adapt practices and goals according to site-specific conditions at different spatial and temporal scales. We propose to create a global research programme that focuses on developing robust SOC management and policies for multiple benefits across terrestrial ecosystems.

Despite current knowledge on SOC processes, there are still multiple uncertainties and challenges for the management of SOC that call for a research action programme. Uncertainties include, but are not limited to: the quantification of synergies between the different benefits of SOC, defining critical thresholds for achieving gains by individual and multiple benefits, and establishing the time frame needed to reach the level required for significant impact on an environmental service. In addition, the significance of change in SOC towards a social benefit is not well understood. Research is needed to measure and assess better the supplies and benefits of SOC for agricultural productivity, water, biodiversity, bioenergy and climate regulation. Other uncertainties of importance include the precise rates of change in SOC, especially across the full rooting zone of the soil system, and the quantification of the impact of future land conversions to agriculture, the abandonment of degraded land and deforestation on SOC. Finally, the lack of methodologies for quantifying the effects of land management and SOC on multiple benefits is a handicap for promoting initiatives towards enhancing SOC stocks. However, these uncertainties should not stand in the way of the critical need to increase SOC and of research that runs across terrestrial ecosystems (Seastedt *et al.*, 2008).

The research community is exploring a wide range of technologies to reduce uncertainty on the benefits of SOC. A variety of geographic information system (GIS) tools and ecosystem models are being used to explore the spatial interactions between services from fields and across landscapes (Hayes *et al.*, 2012; Aide *et al.*, 2013). These tools and models can be used to identify where one service negates the ability to have other services (in the past, agriculture and biodiversity conservation). Such tools could be expanded to include SOC. The key limitations here are effective representation of soil carbon–services relationships, sufficient data to represent these services over space and the capacity to predict changes to interactions over time. While there is evidence of the positive impact of management practices for enhancing SOC on some services such as food production and water quality at local (plot) and catchment level, other services such as climate regulation occur at a larger scale (subnational, regional or global) and are even more difficult to quantify. Despite these uncertainties, failing to act towards increasing SOC on the basis of limited current scientific evidence is much more dangerous than the risks associated with continuous decline in SOC stocks.

Finally, an overriding challenge is the communication between scientists, policy makers and the public. Educating the public about the critical importance of SOC to food, water, bioenergy and climate requires a revolution in communication, specifically about the multiple benefits of SOC for daily life. Translating knowledge of the management and benefits of SOC into communications that inform and engage with societal debates and values can be a key part of the network of scientific and education centres. Therefore, a global research programme to reduce the uncertainty associated with SOC management across terrestrial ecosystems must include a strong educational and outreach component to address practical concerns to different communities outside academia.

Priorities and Actions

We argue that the overall priority is to stop losses of SOC in terrestrial ecosystems. To achieve this goal, we insist that there is a need to create a global research programme to address the challenges and uncertainties associated with increasing SOC for multiple benefits. The fundamental science questions should focus on reducing the uncertainties associated with large-scale assessments and the monitoring of SOC change and benefits at local and global scales. Therefore, urgent actions and new approaches are needed to answer key multi-purpose and multi-scale relationships, thresholds and trade-offs between soil carbon and the essential services (Fig. 2.1). First, we need to understand the recovery rates of SOC better as they are usually non-linear (i.e. have hysteresis effects), making it difficult to forecast the effects of a decision/management made today. Second, research efforts should focus on how to optimize the benefits of soil carbon across various spatial scales where management strategies will vary at the farm/plot, catchment and global level. Third, there is a need to identify the critical ranges/thresholds of SOC losses and recoveries for management purposes and to include the ability to estimate the economic value of investments in soil carbon. All these fundamental research priorities must inform public and economic interests and provide information for policy and actions towards reducing soil carbon losses. Finally, any of these priorities will not be possible without committed long-term funding support and missions by national research agencies and international organizations.

We propose that these research efforts should be linked with specific goals and priorities and actions tailored towards each one of the five essential services (Table 2.1). Here, we discuss specific goals for each essential service.

In order to meet the increasing *food* demand, at both the local and global level, there is a need to increase and sustain food production through better management of soils while improving environment quality. For this, current SOC losses must be stopped and practices to increase SOC must be adopted, including dormant-season cover crops, agroforestry systems, fallows, reduced tillage and applications of mulch, compost and safe biosolids, and in the case of organic soils, paludicultures (Lal *et al*., 2007; Smith *et al*., 2013). Examples include the proposed climate-smart agriculture approach, which

Table 2.1. Summary of wide-scale goals and urgent actions for the five essential services related to soil organic carbon.

Environmental service	Long-term goal	Priority/action
Food	Increase food production	Reduce soil organic carbon losses substantially
Water	Secure sufficient water quantity and quality	Restore hydrological pathways Improve water infiltration Prevent water pollution
Energy	Increase biofuel production	Increase biomass production considering full carbon cycle
Biodiversity	Maintain or enhance below- and aboveground biodiversity	Protect ecological hotspots Restore habitats
Climate	Mitigate climate change	Stop losses of soil organic carbon Increase soil organic carbon

aims at enhancing food productivity while reducing greenhouse gas emissions and enhancing SOC sequestration (FAO, 2013).

In order to enhance *water* quality and quantity, increases in SOC must be targeted to restore hydrological pathways, improve water infiltration management and prevent water pollution (Ahrens *et al.*, 2008; Thomas *et al.*, 2009). Soil and water conservation measures are required to accompany SOC management practices, particularly on sloping lands.

In order to increase immediate *energy production* to meet local demands, we have to focus simultaneously on maximizing the yield of bioenergy crops while preserving or restoring natural ecosystems and soil carbon stocks. Policies on biofuels and the installation of instrumentation for harvesting alternative energy (e.g. wind and solar power) need to be evaluated in light of their effects on soil carbon. For example, the initial conversion of land for biofuel production can result in immediate carbon loss, and the establishment of large deployments of solar and wind power could affect soil carbon storage (Anderson-Teixeira *et al.*, 2012).

In order to enhance *biodiversity*, new management practices that minimize damage and stimulate soil biological activity (e.g. reduced tillage, incorporation of plant residues, cover crops, careful pesticide use) must be applied. In the longer term, we must have sufficient understanding about the global distribution and role of soil biodiversity in ecosystem function, in particular carbon dynamics, to develop and implement sound guidance and policy. Efforts should be targeted towards the protection of ecological hotspots, habitat restoration and maintaining genetic and functional soil biodiversity (Carney and Matson, 2005; Pickles *et al.*, 2012).

To address *climate* change and propose climate mitigation strategies, SOC losses must be minimized through appropriate land-use practices. These include slowing and eventually eliminating the conversion of natural ecosystems such as forest to agricultural uses, slowing and eventually eliminating the use of drained peat soils and slowing and eventually eliminating the use of peat as an energy source and a raw material for horticultural substrates. Increases in soil carbon stocks can be achieved through the careful management of agricultural soils, including the use of reduced tillage, through the implementation of paludicultures on organic soils and through afforestation (Smith *et al.*, 2008; Tschakert *et al.*, 2008; Joosten, 2012).

Furthermore, efforts should be directed to communicate better in new ways to the general public and policy makers the value of increasing SOC. Thus, there is a high priority to increase the communication and education of SOC to permeate into the policy realm and the action plans of local managers/farmers. These actions could lead to public and transparent reports that communicate the state (gains or losses) of SOC and address needs accurately at the local or national scale. In fact, this simple reporting mechanism could be seen as an analogue of the gross domestic product (GDP) used as an economic development indicator. Such mechanism will require new monitoring, verification and reporting schemes for the regulatory, research and economical purposes of soil carbon. This chapter highlights that one of the most significant underlying reasons for lack of investment in SOC is the mismatch between short- and long-term objectives in land management (see also Chapter 4, this volume). It follows that irrespective of the favourable long-term economic case for investment in soil carbon, such investments are unlikely to come about without policy intervention. Soil carbon could be promoted through the payment of ecosystem schemes to reduce the intertemporal trade-offs between short- and long-term objectives. Ultimately, we emphasize that any of these priorities cannot be attained without extensive education efforts on the benefits of SOC to increase public understanding of the need to protect soils around the world.

Conclusions

This chapter has highlighted the need for managing SOC to optimize the mix of five essential services – the provisioning of food, energy and water, regulating climate and maintaining biodiversity (Fig. 2.1). The interaction of SOC with these services shows that they are interconnected and that actions focusing on single services, without considering SOC, impact other services negatively. This calls for a systems approach in order to maximize the benefits on all relevant spatial and temporal scales (Figs 2.3 and 2.4).

We highlight the wide-scale goals and urgent actions towards maximizing the benefits of SOC (Table 2.1) and conclude that the critical priorities are centred on stopping the current losses of SOC. This requires the involvement of various players at local, national and global levels. We propose that in order to quantify better the benefits of SOC, there is a need for complete analyses of the potential actions towards each of the services, including economic, political and environmental implications. Such analyses aim at assessing both the impacts of the actions on each individual service and the co-benefits or adverse impacts on other services. This is needed to maximize SOC gains and to optimize essential services.

We recognize the key uncertainties in managing SOC towards the essential services. However, we conclude that these uncertainties should not stand in the way of the critical need to increase SOC. We propose to take advantage of current scientific knowledge on SOC characteristics, its dynamics and complexity, and managements that affect it, to direct research efforts towards key missing areas and to improve knowledge and practices towards the long-term goals of increasing SOC.

A new vision of soil carbon science that enhances the understanding of the policy and economics of soil services is needed urgently. Such vision will help create a better public understanding of SOC and its societal benefits, which is needed to develop policies that protect soils around the world. Therefore, we call for a global research and education programme focused on the multiple benefits of SOC and with a strong outreach component to share the findings and communicate practical concerns with different communities outside academia. Finally, we recognize that the proposed research and education programme will not be possible without committed long-term funding support.

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