1 The Global Challenge for Soil Carbon

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Abstract

Soil carbon in the form of organic matter is a key component of the soil ecosystem structure. The soil carbon content is an important contributing factor in the many flows and transformations of matter, energy and biodiversity – the essential soil functions that provide ecosystem services and life-sustaining benefits from soil. These goods and services include food production, water storage and filtration, carbon storage, nutrient supply to plants, habitat and biodiversity. Soil functions provide natural capital as a means of production for the ongoing supply of the essential goods and services. Soil carbon content and soil functions are under threat worldwide due to resource demands and the increasing intensification of land use. Land degradation is characterized by soil carbon losses, loss of soil structure and associated loss of fertility, and the physical loss of bulk soil by erosion. Soil carbon accumulation is associated with plant productivity, wet conditions that ensure water supply to vegetation and lack of physical disturbance to the soil. Carbon accumulation is also associated with decreased organic matter decomposition in the soil, created by cool conditions that reduce the rate of microbial activity and wet conditions that create an O_2 diffusion barrier from the atmosphere and reduced aerobic microbial respiration during organic matter decomposition. The environmental conditions for the accumulation of soil carbon also provide important clues to management approaches to reverse soil carbon losses and to increase soil carbon content under widely different environmental conditions around the world. Soil management strategies can be developed from the natural cycling of soil carbon, by reducing physical disturbances to soil, enhancing vegetation cover and productivity and through improved water management. These approaches are essential in order to prevent and reverse the loss of soil functions where land is degraded and to enhance soil functions where actively managed land is undergoing intensification of use. Improved soil carbon management provides an important opportunity in land management worldwide, to meet increasing resource demands and to create resilience in soil functions that arise from the intense pressures of land use and climate change.

Introduction

By 2050, the world's population is expected to reach 9.6 billion (United Nations, 2013). This enormous demographic pressure creates four major global challenges for Earth's soils over the coming four decades.

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This '4 × 40' challenge for global soils is to meet the anticipated demands of humanity (Godfray *et al*., 2010) to:

1. Double the food supply worldwide;
2. Double the fuel supply, including renewable biomass;
3. Increase by more than 50% the supply of clean water, all while acting to
4. Mitigate and adapt to climate change and biodiversity decline regionally and worldwide.

The demographic drivers of environmental change and the demand for biomass production are already putting unprecedented pressure on Earth's soils (Banwart, 2011). Dramatic intensification of agricultural production is central among proposed measures to potentially double the global food supply by 2050. An urgent priority for action is to ensure that soils will cope worldwide with these multiple and increasing demands (Victoria *et al*., 2012).

Soils have many different essential life-supporting functions, of which growing biomass for food, fuel and fibre is but one (Blum, 1993; European Commission, 2006; Victoria *et al*., 2012). Soils store carbon from the atmosphere as a way to mediate atmospheric greenhouse gas levels; they filter contaminants from infiltrating recharge to deliver clean drinking water to aquifers; they provide habitat and maintain a microbial community and gene pool that decomposes and recycles dead organic matter and transforms nutrients into available forms for plants; they release mineral nutrients from parent rock; and they store and transmit water in ways that help prevent floods. These functions underpin many of the goods and services that can lead to social, economic and environmental benefit to humankind. Specific land uses can create trade-offs by focusing on the delivery of one or a few of these functions at the expense of others. Under the pressures of increasingly intensive land use, when decisions are made on land and soil management, it is essential to protect and to enhance the full range of the essential life-sustaining benefits that soils provide.

The build-up of organic matter and carbon is one of the key factors in the development of ecosystem functions as soil forms and evolves. Thus, carbon loss is one of the most important contributions to soil degradation. Furthermore, this central role of carbon across the range of soil functions establishes a buffer function for soil organic matter whereby loss of soil carbon results in a decline in the soil functions, and maintaining or enhancing soil carbon confers resilience to these under pressure from environmental changes (van Noordwijk *et al*., Chapter 3, this volume). In the ensuing chapters of this volume, significant detail is provided to illustrate and quantify the uniquely central role of soil carbon in the delivery of ecosystem services and the opportunity that this presents in managing soil and land use positively to enhance the multiple benefits that soil carbon provides. Set against these opportunities to reverse, conserve and even enhance soil functions is the operational cost implied in the proactive management of soil carbon.

The global soil resource is already showing signs of serious degradation from human use and management. Soil degradation has escalated in the past 200 years with the expansion of cultivated land and urban dwelling, along with an increasing human population. Degradation continues, with soil and soil carbon being lost through water and wind erosion, land conversion that is associated with accelerated emissions of greenhouse gases and the burning of organic matter for fuel or other purposes. Significant degradation has taken place since the industrial revolution; recent and ongoing degradation is substantial; bulk soil loss from erosion remains severe in many locations, with the accompanying loss of soil functions; and the release of carbon and nitrogen from soil as the greenhouse gases CO_2, CH_4 and N_2O continues to contribute to global warming (Table 1.1).

The capacity of soils to deliver ecosystem goods and services which lead to human benefits, and the degree to which these benefits are lost due to soil degradation, varies significantly with geographical location (Plate 1). The global results in Plate 1 provide a first

Table 1.1. Global soil carbon fact sheet. (From Banwart *et al*., 2014.)

Amount of carbon in top 1 m of Earth's soil[b]	2200 Gt
2/3 as organic matter	
Organic C is around 2× greater C content than Earth's atmosphere	
Fraction of antecedent soil and vegetation carbon characteristically lost from agricultural land since 19th century[c]	60%
Fraction of global land area degraded in past 25 years due to soil carbon loss[d]	25%
Rate of soil loss due to conventional agriculture tillage[e]	~1 mm year^{-1}
Rate of soil formation[e]	~0.01 mm year^{-1}
[a]Global mean land denudation rate[f]	0.06 mm year^{-1}
Rate of peatlands loss due to drainage compared to peat accumulation rate[g]	20× faster
Equivalent fraction of anthropogenic greenhouse gas emissions from peatland loss[g]	6% annually
Soil greenhouse gas contributions to anthropogenic emissions, in CO_2 equivalents[h]	25%

[a]Rate of land lowering due to chemical and physical weathering losses; [b]Batjes (1996); [c]Houghton (1995); [d]Bai *et al*. (2008); [e]Montgomery (2007); [f]Wilkinson and McElroy (2007); [g]Joosten (2009); [h]2004 data not including CH_4, IPCC (2007).

indication of the regional and national pressures on soil and the associated trends in the gain or loss of soil functions. What is noteworthy is the broad geographical extent of areas associated with strong degradation.

Soil Carbon in Soil Functions and Ecosystem Services

The process of adding photosynthate carbon to rock parent material and the development of subsurface biodiversity and the formation of soil aggregates is the foundation of soil development and the establishment of soil functions.

Soil forms from parent rock material that is exposed at Earth's surface, receives infiltrating precipitation and is colonized by photosynthesizing organisms (Brantley, 2010): chiefly plants, but also symbiont algae in lichens and photosynthetic cyanobacteria. Organic carbon that is fixed in biomass by photosynthesis is rooted, deposited and mixed and transported by soil fauna into the soil layer, providing carbon and energy for heterotrophic decomposer microorganisms. Other functional groups of microorganisms transform N, P, K and other nutrient elements of decomposing biomass into forms that are available to plants for further biological productivity. Symbiotic fungi that draw energy from plant photosynthate carbon that passes from roots create the pervasive growth of hyphal networks. These proliferate when they encounter nutrient resources such as P- and K-bearing minerals and organic N and P in decomposing plant debris. Grazing and predator organisms including protozoa and soil fauna are sustained by the active microbial biomass. Soil fauna such as worms, termites, ants and other invertebrates play an important role in the initial processing of biomass and for physical mixing and transport through bioturbation, particularly at the surface, but for some organisms throughout the full depth of the soil profile.

Advanced decomposition of biomass by soil organisms yields humic material, which chemically binds to the smallest soil particles with the greatest surface area per mass: clay minerals and Fe and Al oxides. This mineral-adsorbed carbon is chemically more stable and less bioavailable, and produces a hydrophobic coating on the mineral surfaces. The smallest particles aggregate into micron-sized fragments, and decomposition of fresh organic matter by active heterotrophic microorganisms produces microbial extracellular polymers that help bind these intermediate aggregates with rock fragments, decomposing plant debris, biofilms of living microorganisms and fungal hyphae and root surfaces (Tisdall and Oades, 1982; Jarvis *et al*., 2012, and included references). This bound mixture of mineral, dead and living biomass and pore fluids, forms larger aggregates, resulting in a system called soil structure, which produces a pore volume distribution that allows both water storage in small throats and pores and free drainage of water and ingress of atmospheric O_2, to support root and microbial respiration, through connected networks of larger pores.

Soil organic matter and soil carbon are thus central to all of the underpinning physical, chemical and biological processes of soil functions. At the landscape scale, the resulting transformations and flows of material, energy and genetic information are delivered as ecosystem services that provide enormous benefits for humans (Fig. 1.1). This view of the environment is embodied in the concept of soil as natural capital that provides a means of production for the ongoing supply of beneficial goods and services (Robinson *et al.*, 2013). Indeed, Robinson *et al.* (2013) noted soil carbon, along with soil organisms, embodied biogeochemical energy and the structural organization of soil as the key components of this natural capital. This view is broadly held through the following chapters of this volume and inherently introduces an anthropocentric view of natural processes that describes these in terms of economic services with an instrumental value for human well-being. The latter is not analysed explicitly, but this departs from a broader biocentric perspective of the intrinsic value of Earth's environment and the ongoing processes that it supports.

Drawing on the concepts of ecosystem services within the Millennium Ecosystem Assessment defines the following services arising from soil functions (MEA, 2005; Black *et al.*, 2008; Robinson *et al.*, 2013).

1. Supporting services are the cycling of nutrients, the retention and release of water, the formation of soil, provision of habitat for biodiversity, the exchange of gases with the atmosphere and the degradation of plant and other complex materials.

2. Regulating services for climate, stream and groundwater flow, water and air quality and environmental hazards are: the sequestration of carbon from the atmosphere, emission of greenhouse gases, the filtration and purification of water, attenuation of

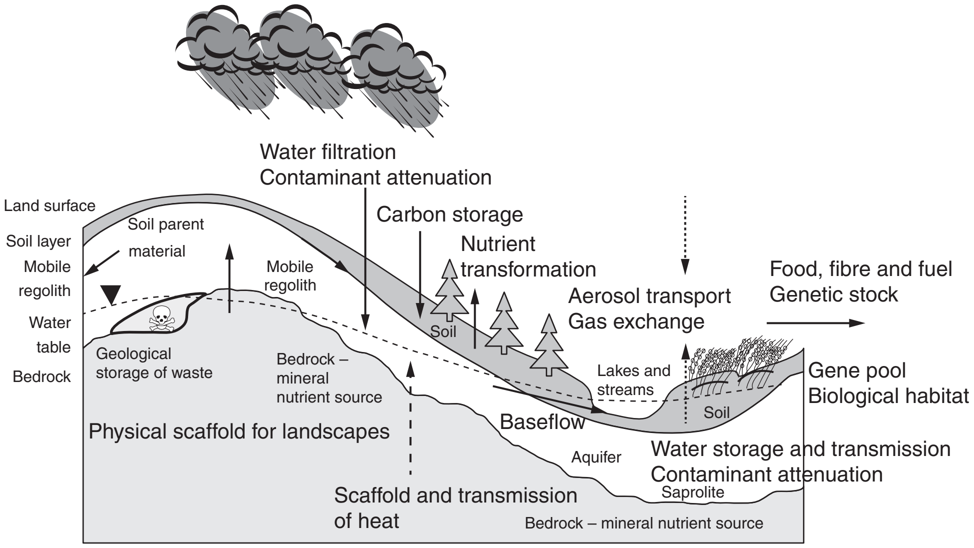

Fig. 1.1. Soil functions and ecosystem services are at the heart of Earth's critical zone; the thin outer layer of the planet that supports almost all human activity. Within this hill slope diagram, the arrows illustrate important flows of material, energy and genetic information that support ecosystem services and provide essential benefits. These flows create a chain of impact that propagates changes in the aboveground environment (e.g. changing climate, land use), via the soil layer, throughout the critical zone. Thus, considering decisions that affect soil requires understanding consequences along the entire chain of impact; and the full consideration of all costs and benefits whether intended or not. (From Banwart *et al*., 2012.)

pollutants from atmospheric deposition and land contamination, gas and aerosol emissions, slope and other physical stability, and storage and transmission of infiltrating water.

3. Provisioning services are food, fuel and fibre production, water availability, non-renewable mineral resources and as a platform for construction.

4. Cultural services are the preservation of archaeological remains, outdoor recreational pursuits, ethical, spiritual and religious interests, the identity of landscapes and supporting habitat.

Soil carbon plays a key role in all four classes of soil ecosystem services. The flows arising from environmental processes (Fig. 1.1) depend on ecosystem structure, where soil carbon is a key component, along with the environmental conditions and human interventions that can influence the produced services, goods and benefits strongly (Fig. 1.2; Fisher *et al.*, 2009; Bateman *et al.*, 2011; Robinson *et al.*, 2013).

Subsequent chapters delve into the underlying processes, the impacts of environmental change, the chains of impact and the consequences that arise, and methods to intervene in order to influence these impacts beneficially. Decisions on land use and soil management that affect the stocks and composition of soil carbon therefore incur costs and benefits through changes to these ecosystem services. In many cases, the value of these changes is not reflected in markets,

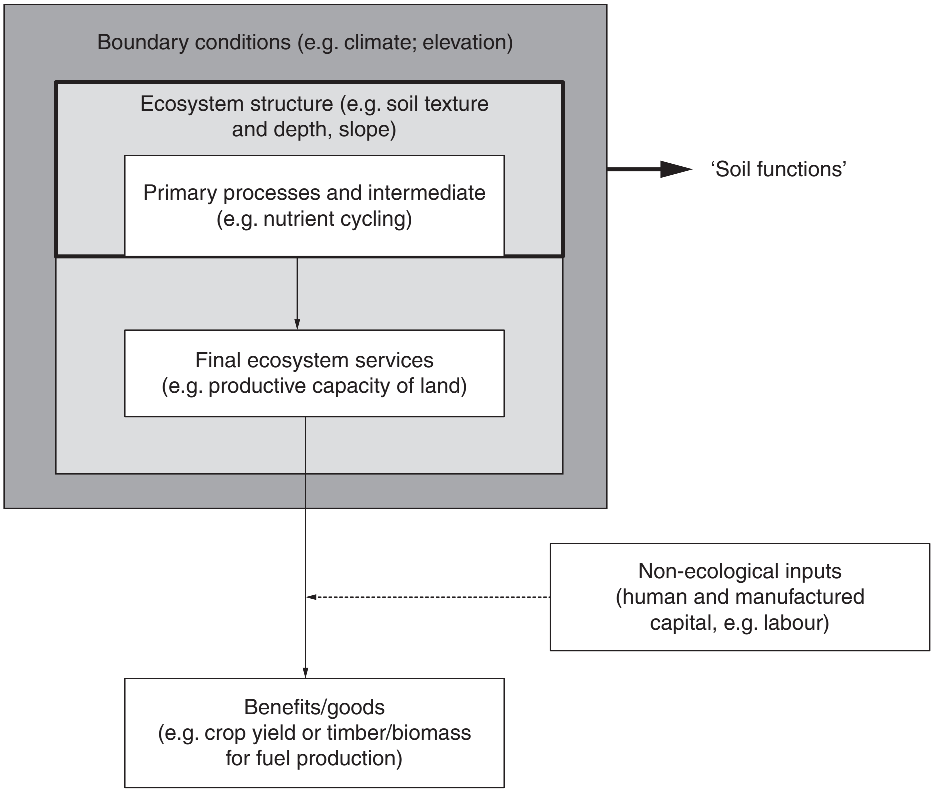

Fig. 1.2. Conceptual linkages between environmental drivers, ecosystem structure (cf. Fig. 1.1) including soil conditions, the soil processes that produce the environmental flows that characterize soil functions and their potential to provide ecosystem services, goods and benefits. (Adapted from Fisher *et al*., 2009 and Bateman *et al*., 2011.)

such that management decisions are made without full information on the consequences of change. Such market and informational failure necessarily leads to the suboptimal allocation of effort to conserve soil from a social perspective. The failure of markets and policy to prevent soil carbon loss and land degradation is therefore a key component of the global challenge to provide sufficient life-sustaining resources.

Threats to Soil Carbon

The global stocks of soil carbon are under threat (Table 1.1 and Plate 1), with consequences for the widespread loss of soil functions and an increase in greenhouse gas emissions from land and acceleration of global warming (Lal, 2010a,b). In many locations, soil functions are already compromised. Some of the consequences include increased erosion, increased pollution of water bodies from the N and P loads that arise from erosion, desertification, declining fertility and loss of habitat and biodiversity. The primary control on the global distribution of soil carbon is rainfall, with greater accumulation of soil organic matter in more humid regions. A secondary control is temperature, with greater organic matter accumulation in colder regions when otherwise sufficiently humid conditions persist regardless of temperature. Under similar climatic conditions, wetter soils help to accumulate soil carbon by limiting rates of microbial respiration (Batjes, 2011), since O_2 ingress is restricted by the gas diffusion barrier created by greater water content. Relatively drier conditions favour O_2 ingress and aeration of soil, thus accelerating soil carbon decomposition. Furthermore, physical disturbance such as tillage breaks up larger soil aggregates and exposes occluded carbon within aggregates to O_2 and biodegradation, thus creating conditions that allow greater soil carbon loss.

With sufficient water, nutrients and O_2 supply, biological processes are relatively faster at higher temperature; hence, greater rates of productivity and decomposition. Thus, warm, humid conditions favour soil carbon accumulation due to high productivity, while cool, humid conditions favour soil carbon accumulation due to low decomposition rates. Soil carbon varies substantially geographically with land cover (Plate 2). For example, savannah has relatively low soil carbon content but covers a large area globally. On the other hand, peatlands have extremely high carbon content but cover less than 0.3% of the global land surface. By inspection of Plates 1 and 2, it is clear that degraded land coincides in large part with Earth's drylands, due to low productivity from low water availability and relatively high decomposition due to dry, well-aerated and warm soils.

From these controls on soil carbon content, it is clear that predicted changes to regional as well as global climate in the coming decades will create important impacts on soil carbon (Schils *et al*., 2008; Conant *et al*., 2011). Drier, warmer conditions are expected to coincide with greater potential for loss of soil carbon and the associated loss of soil functions. Loss of permafrost will expose accumulated carbon in cold regions to much greater rates of microbial decomposition (Schuur and Abbot, 2011). Furthermore, the demographic drivers of more intensive land use raise the prospect of greater physical disturbance of soils, e.g. tilling of grasslands. More intense tillage and greater areas of mechanical tillage are expected to coincide with higher loss of soil carbon due to greater exposure of soil carbon to O_2 (Powlson *et al*., 2011).

Managing Soil Carbon for Multiple Benefits

Maintaining and increasing soil carbon content yields substantial multiple benefits. Greater soil carbon helps to maintain soil structure by forming stable larger aggregates and larger inter-aggregate pores that create greater soil permeability and drainage for root growth. Smaller interior pores within aggregates, on the other hand, provide water-holding capacity to sustain biological processes. Increasing soil carbon provides carbon and energy to support microbial activity, provides a reservoir of organic N, P and other nutrients for plant productivity and creates more physically cohesive soil to resist soil losses by physical erosion and by protecting occluded organic matter within the larger aggregates. Carbon that enters soil is removed from the atmosphere; any gains in soil carbon mitigate greenhouse gas emissions, with caveats about impacts on the N cycle and N_2O production and the production of CH_4 from the anaerobic decomposition of organic matter in waterlogged soils.

The factors that control soil carbon levels offer clues to strategies that can maintain and increase soil carbon content. Increasing carbon levels may be achieved by reducing soil carbon losses by measures to reduce physical erosion by wind or overland water flow, measures to prevent the mechanical disturbance of aggregates and measures to increase the water content of organic soils. Increasing input of soil carbon can be achieved by measures that increase the aboveground production of vegetation, the increased allocation of carbon below ground through greater root density and associated carbon input and microbial biomass, increased plant residue return to soil and the addition of imported organic matter such as compost.

Soil carbon is lost rapidly when soils are disturbed through land-use conversion from grassland and forest to arable, and when land is drained. However, building up soil carbon is slow. The risks of losing soil carbon are great because of the potential consequences of:

- the loss of soil fertility and agricultural production;
- increased greenhouse gas emissions and accelerated climate change; and
- diminished soil functions across the full range of the ecosystem services described above.

There is considerable knowledge and data on the role of soil organic matter in specific soil functions, particularly related to biomass production, water and contaminant filtration, and CO_2 emissions. There is considerably less known about the interactions between soil organic matter, biodiversity, transformations of nutrients and soil structure, and the physical stability of soil structure and aggregates. The knowledge of the role of soil carbon, and the existing methods and innovation potential to manage it effectively for this wide range of benefits, is collectively substantial but is fragmented between many different disciplines. The subsequent chapters of this volume seek to summarize this wide knowledge base and showcase regional examples of beneficial management of soil carbon with the potential to expand such practices greatly worldwide.

Beneficial management of soil carbon offers the opportunity not only to avoid the negative consequences but also to enhance the wide range of available soil functions and ecosystem services. For these reasons, policies are essential that encourage protecting, maintaining and enhancing soil carbon levels.

A new focus on soil carbon at all levels of governance for soil management would better enable the full potential of soil ecosystem services to be realized. This advance is urgent and essential. To meet successfully the '4 × 40' challenge laid out in the introduction (Godfray *et al.*, 2010), there is significant opportunity through soil carbon management to help meet the demand for food, fuel and clean water worldwide. It is also an essential step towards soil management that establishes enhanced soil functions that last – in order to meet the needs of future generations; not only to meet the demands anticipated in the coming four decades.

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