FutureDirections international

INDEPENDENT STRATEGIC ANALYSIS OF AUSTRALIA'S GLOBAL INTERESTS

Strategic Analysis Paper

18 May 2017

The Role of Carbon in Promoting Healthy Soils[1]

Christopher Johns
Research Manager
Northern Australia and Landcare Research Programme

Key Points

- Soils have become one of the most vulnerable resources in the world.
- The huge carbon reservoir found in soil is not static but is constantly cycling between the different global carbon pools in various forms.
- Soils are a key reservoir of global biodiversity (the variety of plant and animal life in a specific habitat) which has a fundamental role in supporting soil functions.
- Water stored in soil serves as the source for 90 per cent of the world's agricultural production and represents about 65 per cent of global fresh water.
- Soil organic carbon plays an essentially important role in ensuring global food security.

Summary

As the effects of land degradation, biodiversity loss and climate change become increasingly severe, soils have become one of the most vulnerable resources in the world. Soils are a major carbon reservoir containing more carbon than the atmosphere and terrestrial vegetation combined. Soil organic carbon (SOC) is dynamic, however, and human impacts on soil can turn it into either a net sink or a net source of atmospheric greenhouse gases (GHG). Enormous scientific progress has been achieved in understanding and explaining SOC dynamics. Protection and monitoring of SOC stocks at national and global levels, however, still face complicated challenges impeding effective on-the-ground policy design and regionally adapted implementation.

[1] The principle reference for this Strategic Analysis Paper is *Soil Organic Carbon: the hidden potential*, FAO, Rome, 2017.

After carbon enters the soil in the form of organic material from soil flora and fauna, it can persist in the soil for decades, centuries or even millennia. Eventually, SOC can be lost as carbon dioxide (CO_2) or methane emitted back into the atmosphere, becoming eroded soil material, or by being dissolved as organic carbon and washed into rivers and oceans. The dynamics of these processes highlight the importance of quantifying global carbon fluctuations to ensure maximum benefits of SOC to human well-being, food production and water and climate regulation.

SOC is the main component of soil organic matter (SOM). As an indicator for soil health, SOC is important for its contribution to food production, as mitigation and adaptation to climate change and the achievement of the sustainable development goals. A high SOM content provides nutrients to plants and improves water availability, both of which enhance soil fertility and ultimately improve food productivity. Moreover, SOC improves soil structural stability by promoting aggregate formation which, together with porosity, ensure sufficient aeration and water infiltration to support plant growth. With an optimal amount of SOC, the water filtration capacity of soils further supports the supply of clean water. Through accelerated SOC mineralisation, soils can be a substantial source of GHG emissions into the atmosphere. Although the overall impact of climate change on SOC stocks is very variable according to the region and soil type, rising temperatures and increased frequency of extreme events are likely to lead to increased SOC losses.

Globally, SOC stocks are estimated at an average of 1500 peta-grams of carbon (PgC) (**one peta-gram of Carbon equals one billion metric tonnes**) in the first meter of soil, although their distribution is spatially and temporally variable. SOC hot-spots and bright spots, which are respectively areas of high SOC content (e.g. peatlands or black soils) and large surface areas of low SOC content (e.g. drylands) constitute major zones of concern. With climate change and unsustainable management, these areas are likely to become net sources of GHG emissions. When managed wisely, however, they have the potential to sequester large amounts of carbon in their soils, thus contributing to climate change mitigation and adaptation.

Analysis

Introduction

The element carbon exists in the soil in many forms, but for the purposes of this discussion there are three main forms as introduced below.

Soil organic carbon, SOC, is derived from living tissue: plant leaves and roots, sap and exudates, microbes, fungi, and animals. It takes a bewildering variety of complex chemical forms, many of which remain unclassified. Much of it is a result of decay processes and microbial metabolisms. **Soil organic matter, SOM,** is a generic or common name. It contains 50 to 58 percent carbon by dry weight.

SOM holds many times its weight in water. Its critical sticky components play a vital role in the formation of soil aggregates which give soil its stability against weathering and erosion, and its ability to hold water and air essential for plants and microbes.

SOM may be the most valuable form of soil carbon, but is generally the least stable, though some forms may persist for a thousand years and more. Many forms can be readily oxidized (turned into carbon dioxide) by common bacteria in the presence of oxygen. But it is also the form of soil carbon that can readily increase because of plant growth, the root shedding of perennial grasses, the incorporation of manure or compost, the liquid carbohydrate exudates of plant roots, all processed by microbial metabolisms. Soil organic matter is the most abundant form of soil carbon.

Charcoal also derives from living tissue, so it is considered organic. It is often called biochar. It can range from 50 to 95 percent carbon by weight. It is more stable and more resistant to bacterial oxidation than most other forms of organic carbon, which is one reason why there is considerable interest in incorporating biochar into soil as a carbon sequestration strategy.

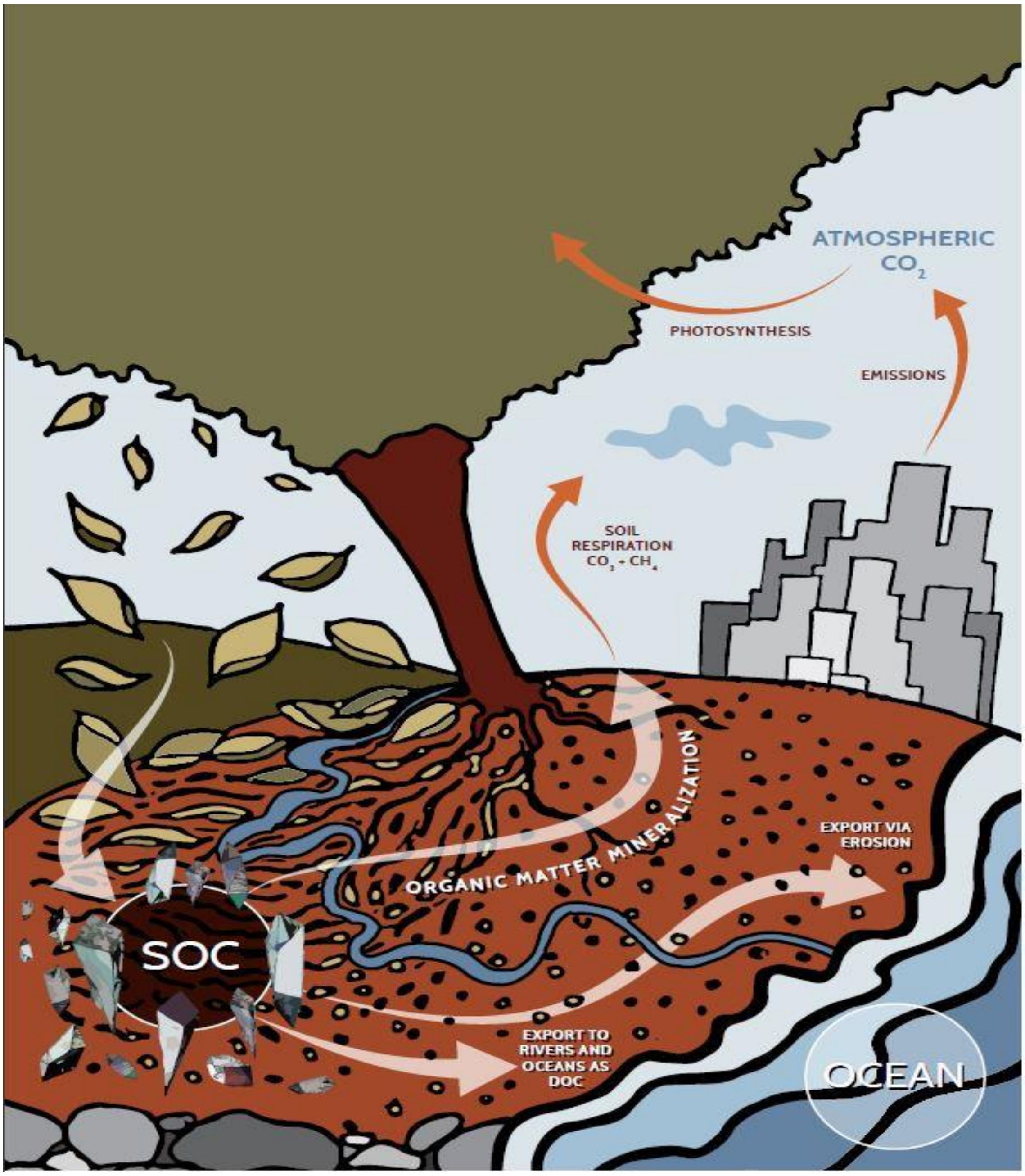

Figure1. Soil Organic Carbon as a component of the global carbon cycle. Source: FAO.

Soil inorganic carbon is mineralized forms of carbon, such as calcium carbonate, or caliche. It is more stable than most organic carbon because it does not provide food or fuel for microorganisms. Carbonates are common in more arid regions and alkali soils, and are a significant soil carbon pool worldwide, derived mostly from organic carbon fixed by photosynthesis.

Inorganic carbon, while it does not possess the water-holding and soil-enhancing properties of organic carbon, is nevertheless a significant store for atmospheric carbon, though it typically changes at a slower rate.

The analysis to follow deals principally with SOC as a component of SOM and its capacity to influence soil health, promote food security and mitigate climate change.

Soil Organic Carbon as a Component of Soil Organic Matter

The term SOM is used to describe the organic constituents in soil in various stages of decomposition such as tissues from dead plants and animals, materials less than 2mm in size, and soil organisms. SOM turnover plays a crucial role in soil ecosystem functioning and global warming. SOM is critical for the stabilisation of soil structure, retention and release of plant nutrients and maintenance of water-holding capacity, thus making it a key indicator not only for agricultural productivity, but also environmental resilience. The decomposition of SOM further releases mineral nutrients, thereby making them available for plant growth, while better plant growth and higher productivity contribute to ensuring food security.

SOM can be divided into different pools based on the time needed for full decomposition and the derived residence time of the products in the soil (turnover time) as follows:

- Active pools - turnover in months or few years;
- Passive pools - turnover in up to thousands of years.

Long turnover times of organic compounds are not only explained by oxygen free conditions such as in peats, but also by incorporation of SOM components into soil aggregates, attachment of organic matter to protective mineral surfaces, the separation between SOM and decomposers and the intrinsic biochemical properties of SOM. Microaggregates are considered responsible for the stabilisation of the passive pools (permanent stabilising agents), whereas macroaggregates and clods encapsulating small aggregates are considered transient stabilising agents. This physical and chemical stabilisation of SOM hinders, to different degrees, microbial decomposition via restricted mobility and access of microbes to organic matter, as well as diffusion of water, enzymes and oxygen. In addition, such stabilisation requires a broad range of microbial enzymes to degrade the insoluble macromolecules that comprise SOM.

SOM contains roughly 55 to 60 per cent carbon by mass. In many soils, this carbon comprises most or all the carbon stock – referred to as SOC – except where inorganic forms of soil carbon occur.

Like SOM, SOC is divided into different pools as a function of its physical and chemical stability:

- Fast pool (active or labile pool) - After addition of fresh organic carbon to the soil, decomposition results in a large proportion of the initial biomass being lost in 1–2 years.
- Intermediate pool - Comprises microbially processed organic carbon that is partially stabilised on mineral surfaces and/or protected within aggregates, with turnover times in the range from 10 to 100 years.
- Slow pool (refractory or stable pool) - highly stabilised SOC, enters a period of very slow turnover of 100 to over 1000 years.

An additional slow SOC pool is pyrogenic SOC (charcoal), formed from partially carbonised (e.g., pyrolyzed) biomass during wildfires which is present in many ecosystems. A portion of this material has a highly condensed aromatic chemical structure (often referred to as pyrogenic carbon or black carbon) that resists microbial degradation and thus persists in soils for long periods.

The separation of SOC into different pools is largely general and not measurable in exact amounts with definitive boundaries. Although SOC pools are often used to model carbon dynamics, ways to reconcile "measurable" and "modellable" pools have rarely been reported. SOC and SOM should therefore also be considered a continuum of organic material in all stages of transformation and decomposition or stabilisation.

The proportion of labile SOC to total SOC influences SOC sequestration and soil health. The labile carbon fraction has been shown to be an indicator of key soil chemical and physical properties. For example, this fraction was found to be the primary factor controlling aggregate breakdown in Ferrosols (non-cracking red clays), measured by the percentage of aggregates measuring less than 0.125 mm in the surface crust after simulated rain in the laboratory. The resistant or stable fraction of SOC contributes mainly to the soil's nutrient holding capacity. Additionally, because this fraction of organic carbon decomposes very slowly, it is especially interesting in terms of long-term SOC sequestration.

What is Soil Organic Carbon?

SOC is one part in the much larger global carbon cycle that involves the cycling of carbon through the soil, vegetation, ocean and the atmosphere. The SOC pool stores an estimated 1 500 PgC in the first meter of soil, which is more carbon than is contained in the atmosphere (roughly 800 PgC) and terrestrial vegetation (500 PgC) combined. This huge SOC reservoir is not static, but is constantly cycling between the different global carbon pools in various forms.

SOC enters the soil in several ways. CO_2 and methane are the main carbon-based atmospheric gases. Organisms, mainly plants and microbes, synthesise atmospheric CO_2 into organic material by processes such as photosynthesis. Dead organic material (mainly in the form of plant residues) is incorporated into the soil by soil fauna such as earthworms and insects. This, in turn, leads to carbon inputs into the soil through transformation by microorganisms. This results in a complex mixture of plant litter compounds and microbial decomposition products in various stages of decomposition that can be associated with soil minerals and sealed within soil clumps or aggregates, enabling SOC to persist in soil for decades, centuries or even millennia.

CO_2 is emitted back into the atmosphere when SOM is decomposed or otherwise broken down by microorganisms. Soil carbon loss can also be caused by root exudates such as oxalic acid, which liberate organic compounds from protective mineral associations. Finally, carbon is also partly exported from soils to rivers and oceans as dissolved organic carbon (DOC) or as part of erosion material.

In principle, the amount of SOC stored in each soil is dependent on the equilibrium between the amount of carbon entering the soil and the amount of carbon leaving the soil as carbon-based respiration gases resulting from microbial activity and, to a lesser extent, leaching from the soil as DOC. Locally, carbon can also be lost or gained through soil erosion or deposition, leading to the redistribution of soil carbon at local, landscape and regional scales. Levels of SOC storage are therefore mainly controlled by managing the amount and type of organic residues that enter the soil (i.e. the input of organic carbon to the soil system) and minimising the soil carbon losses. Factors controlling the decomposition of organic matter in soil include soil temperature and water content (mainly determined by climatic conditions) which greatly influence soil carbon storage through their effect on microbial activity. The composition of the microbial community may also have an influence on the preferential decomposition of certain compounds. The presumed chemical recalcitrance of complex molecules that build up SOC, such as lignin or lipids, does not substantially contribute to SOM persistence in soil. SOM persistence is rather affected by SOC stabilisation in the soil through its interaction and association with soil minerals.

Influence of SOC on Water-Holding Capacity and Porosity

Organic matter improves soil aggregate and structural stability which, together with porosity, are important for soil aeration and the infiltration of water into soil. While plant growth and surface mulches can help protect the soil surface, a stable, well-aggregated soil structure that resists surface sealing and continues to infiltrate water during intense rainfall events will decrease the potential for downstream flooding. Porosity determines the capacity of the soil to retain water and controls transmission of water through the soil. In addition to total porosity, the continuity and structure of the pore network are important to these functions and to the further function of filtering out contaminants. Finally, the water stored in soil serves as the source for 90 per cent of the world's agricultural production and represents about 65 per cent of global fresh water.

SOC and Biodiversity

Soil biodiversity reflects the mix of living organisms in the soil. These organisms interact with one another, as well as with plants and small animals, forming a web of biological activity. On the one hand, soil biodiversity contributes greatly to the formation of SOM from organic litter, thereby contributing to the enhancement of SOC content. On the other hand, the amount and quality of SOM (and consequently SOC) determines the number and activity of soil biota that interact with plant roots. Therefore, the soil microbial community structure is influenced largely by the quality and quantity of SOC and to a lesser extent by plant diversity.

Importance of Soil Biodiversity

The broad importance of biodiversity was formalised in the United Nations Convention on Biological Diversity established in 1992. Biodiversity ensures ecosystem functioning, and each organism, irrespective of its size, has an important role to play. In 2015, the Revised World Soil Charter stated that:

> *Soils are a key reservoir of global biodiversity, which ranges from micro-organisms to flora and fauna. This biodiversity has a fundamental role in supporting soil functions and therefore ecosystem goods and services associated with soils. It is therefore necessary to maintain soil biodiversity to safeguard these functions*.

Soil biodiversity (including organisms such as bacteria, fungi, protozoa, insects, worms, other invertebrates and mammals), combined with SOC, shape the life supporting capacity of soils and is believed to play a crucial role in increasing food production and soil resilience to change. Complex soil organism communities contribute to the following:

- determine the magnitude and direction of carbon fluctuations between the atmosphere and soils (either by supporting soil carbon sequestration or by enhancing GHG emissions);
- cycle SOC and significantly influence nutrient availability (in particular, nutrient acquisition by plants is highly effective when supported by associations with soil microorganisms);
- improve soil physical structure by promoting aggregation; and
- promote biological pest control and crop pollination.

Many scientists have reported the role of macro-fauna in the accumulation of SOC. For example, millipedes and earth-worms breakdown and transform particulate organic matter. The larger soil animals can also move SOC to greater soil depths where it is believed to remain for longer periods of time.

Soil Biodiversity Losses

Losses in soil biodiversity have been demonstrated to affect multiple ecosystem functions including decomposition of SOC, nutrient retention and nutrient cycling. Poor land-management practices and environmental change are affecting belowground communities globally, and the resulting declines in soil biodiversity reduce and impair these benefits.

The unsustainable agricultural management practiced in many agricultural ecosystems (such as monocultures, extensive use of tillage and chemical inputs) degrade the fragile web of community interactions between pests and their natural enemies, thus having negative repercussions on SOC stocks. When losses of SOC cannot be fully explained by physical soil properties, it is hypothesised that the stability of SOC is dependent on the activity and diversity of soil organisms.

With ongoing losses in belowground microbial diversity, understanding relationships between soil biodiversity and carbon cycling is critical for projecting how the loss of diversity under continued environmental alteration by humans will impact global carbon cycling processes.

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 underutilised resource with the ability to ultimately improve human health. For sustainable soil management techniques aimed at climate change mitigation and adaptation and sustainable food production.

SOC Food Production and Water Supply

Soil Fertility and Food Production

Soil fertility refers to the ability of soil to support and sustain plant growth, including through making nitrogen, phosphorous, sulphur, and other nutrients available for plant uptake. This process is facilitated by:

- nutrient storage in SOM;
- nutrient recycling from organic to plant-available mineral forms; and
- physical and chemical processes that control nutrient absorption, availability, displacement and eventual losses to the atmosphere and water.

Managed soils represent a highly dynamic system, and it is this very dynamism that makes soils function and support ecosystems. Overall, the fertility and functioning of soils depend on interactions between the soil mineral composition, plants and microbes. These are responsible for both building and decomposing SOM and, therefore, for the preservation and availability of nutrients in soils. To sustain soil functions, the balanced cycling of nutrients in soils must be maintained.

SOC Management for Sustainable Food Production

It is widely recognised that SOC sequestration can be of great importance as a climate change mitigation and adaptation measure. It is often over looked, however, that SOC plays an equally important role in ensuring food security. This is achieved by enhancing soil productivity and maintaining consistently high yields, particularly by increasing water and nutrient holding capacity and improved soil structure, thus improving plant growth conditions.

Climate change is likely to have a strong impact on agriculture, thus posing a major threat to food security. Credible research projections foresee the possibility of a 4°C temperature increase by the end of the 21st century. Should this occur, environmental repercussions could be devastating for food security given the increasing global food demands. Climate change is one of the major challenges that the world's agricultural sector faces in meeting the global food requirements. Food security in relation to climate change is affected in four different dimensions:

- food availability;
- food accessibility;
- the stability of food supply; and
- the ability of consumers to adequately utilise food (food safety and nutrition).

Climate change, as evidenced by increasing temperatures, changing precipitation patterns and more frequent and extreme weather events, tremendously impacts crop and livestock production. Furthermore, increasing water body temperatures and increasing levels and changes in current sea productivity patterns most affect fishery and aquaculture production. Consequently, major drawbacks are expected which include yield reductions, biological migration, declines in agrobiodiversity and ecological services, loss of agricultural incomes and increases in food prices and trading costs. Therefore, there is a drive to implement and improve measures that alleviate these risks to global food security. As vital as it is for climate change mitigation and adaptation, SOC is key for ensuring a consistent global food supply.

SOC content is one of the key soil properties associated with many soil functions. It is a source of nutrients and is crucial for agricultural production. Increases in SOC stock increases crop yields in high-input commercial agriculture, but especially in low-input degraded land. In areas like sub-Saharan Africa, where subsistence farmers experience deficiencies in fertiliser availability and proper irrigation, SOC is the key for increased production.

Many studies have quantified the contributions of SOC in terms of food production. The adoption of SOC conserving agricultural practices can increase food production by 17.6 Mt/year. Research indicates that a 1 tonne increase in the SOC pool of degraded cropland can increase wheat yields by 20-40kg per hectare, maize by 10-20 kg per hectare, and cowpeas by 0.5kg per hectare. Sustainable soil management that increases SOC stocks should be developed on a local and global basis, and should be adopted for more sustainable food systems.

SOC Sequestration

Soil organic carbon sequestration is the process by which carbon is fixed from the atmosphere via plants or organic residues and stored in the soil. When dealing with CO_2, SOC sequestration involves three stages:

- the removal of CO_2 from the atmosphere via plant photosynthesis;
- the transfer of carbon from CO_2 to plant biomass; and
- the transfer of carbon from plant biomass to the soil where it is stored in the form of SOC in the most least stable or labile carbon pool.

This pool is characterised by the highest turnover rate (days to a few years), encompasses recently incorporated plant residues and is readily decomposable by soil fauna, generally causing CO_2 emissions back into the atmosphere. Therefore, imperative SOC sequestration action planning requires looking beyond capturing atmospheric CO_2, and necessitates finding ways to retain carbon in the slow SOC pool. Contrastingly, research shows that the stable pool has a negligible potential for carbon sequestration due to its resistance to change and hence, irresponsiveness to management.

Newly added carbon can be stabilised in the soil by several mechanisms. Physically, carbon may be stabilised via its isolation inside soil micro and macro aggregates where it is inaccessible to soil organisms and oxygen. Chemically, carbon may be strongly bonded to clays which prevents the consumption of carbon by organisms. Biochemically, carbon may be re-synthesised into complex molecule structures that may hinder decomposition. The three mechanisms depend on several biological, non-biological and management factors that shape their soil carbon stabilisation efficacy.

The concept of soil carbon saturation implies that the soil carbon stock has reached its maximum carrying capacity for storing soil carbon inputs. This threshold, which depends on many factors including inherent and dynamic soil properties and their interactions with abiotic factors, is also referred to in literature as the maximum carbon stabilisation capacity. It infers that soil carbon stabilisation curves are not infinitely increasing, and that when a carbon saturation level is reached, SOC sequestration comes to an end, soils stop being a net carbon sink and may become a net carbon source. As such, SOC sequestration has spatial and temporal limitations and is a reversible process. Soils that are depleted of SOC have the greatest potential to gain carbon, but also have the least propensity to do so. Since most soils around the world are far from their saturation thresholds, there is great potential for increased carbon inputs and management that protects existing stocks to maximise soil carbon sequestration.

In general, carbon cycling and carbon sequestration is most active in topsoil, whereas stabilised carbon with longer turnover times makes up a greater proportion of the total SOC found in deep soils. It is estimated that soils at greater depth have a higher capacity of storing additional carbon compared to topsoils because of a larger difference between the existing SOC content and the SOC saturation value. The accumulation of stabilised carbon with long residence times in deep soil horizons may be due to continuous transport, temporary immobilisation and microbial processing of DOC within the soil profile and/or efficient stabilisation of root-derived organic matter within the soil matrix emphasised that subsoils have the potential to store 760-1520 Pg additional carbon.

At the same time, it was pointed out that care should be taken when adding new carbon sources to subsoils because of the risk of enhanced mineralisation of existing SOC. Nevertheless, increasing SOC stocks in subsoil is still recognised as a promising means to enable substantial carbon sequestration in soils.

Conclusion

Within the Framework of the United Nations Framework Convention on Climate Change, international agreements such as the Kyoto Protocol and the Paris Agreement have set the rules for GHG emission targets, as well as the necessity to regularly report on manmade GHG emissions. As part of these efforts, accurate inventories on emissions due to SOC stock changes should be reported. The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for measuring, reporting and verifying national SOC stock inventories following the Monitoring, Reporting and Verifying (MRV) Framework which ensures that these inventories fulfil the criteria of completeness, transparency, consistency, accuracy and thus comparability. To achieve greater specificity and accuracy, improved methods are required to measure, account, monitor and report on this specific carbon pool.

Climate change, manmade or not, poses a major threat to food security through its strong impact on agriculture. It is thought to negatively affect crop, livestock and fishery production through yield reductions, biological migration and loss of ecosystem services, which ultimately lead to a reduction in agricultural incomes and an increase in food prices. SOC sequestration can support the mitigation of these issues while offering part of the solution to a warming climate. Therefore, several suggested SOC conserving practices need to be implemented to reach the maximum potential of climate change mitigation and adaptation and food productivity. Barriers exist, however, to adopting these practices. Financial, technical, logistic, institutional, knowledge, resource and socio-cultural barriers and their interactions all influence our capacity to change. When these barriers are combined with physical factors which restrict SOC build-up, they prevent the adoption of climate change mitigation and adaptation practices. Despite some recognised solutions to overcome human induced barriers, global adoption rates of sustainable soil management practices remain below the level necessary to achieve international goals.

*****

Any opinions or views expressed in this paper are those of the individual author, unless stated to be those of Future Directions International.

Published by Future Directions International Pty Ltd.
80 Birdwood Parade, Dalkeith WA 6009, Australia.
Tel: +61 8 9389 9831 Fax: +61 8 9389 8803
Web: www.futuredirections.org.au