The Benefits of Soil Carbon

Managing soils for multiple economic, societal and environmental benefits

In view of the growing world population, within two decades global demand for food is projected to increase by 50 per cent, demand for water by 35-60 per cent, and demand for energy by 45 per cent. The world’s soils are consequently under increasing pressure. Soil carbon plays a vital role in regulating climate, water supplies and biodiversity, and therefore in providing the ecosystem services that are essential to human well-being. Managing soils to obtain multiple economic, societal and environmental benefits requires integrated policies and incentives that maintain and enhance soil carbon. Decisive action needs to be taken to limit soil carbon loss due to erosion and emissions of carbon dioxide and other greenhouse gases to the atmosphere.

The top metre of the world’s soils stores approximately 2200 Gt (billion tonnes) of carbon, two-thirds of it in the form of organic matter (Batjes 1996). This is more than three times the amount of carbon held in the atmosphere. However, soils are vulnerable to carbon losses through degradation (Figure 1). They also release greenhouse gases to the atmosphere as a result of accelerated decomposition due to land use change or unsustainable land management practices (Lal 2010a, b).

In the face of further land use intensification to meet global demand for food, water and energy (Foresight 2011), managing soils so that carbon stocks are sustained and even enhanced is of crucial importance if we are to meet near-term challenges and conserve this valuable resource for future generations. Since the 19th century, around 60 per cent of the carbon in the world’s soils and vegetation has been lost owing to land use (Houghton 1995). In the past 25 years, one-quarter of the global land area has suffered a decline in productivity and in the ability to provide ecosystem services because of soil carbon losses (Bai et al. 2008).

Soil erosion associated with conventional agricultural practices can occur at rates up to 100 times greater than the rate at which natural soil formation takes place (Montgomery 2007). Peatland drainage worldwide is causing carbon-rich peat to disappear at a rate 20 times greater than the rate at which the peat accumulated (Joosten 2009).

Agriculture on drained peatland in Central Kalimantan, Indonesia, is leading to huge soil carbon losses. Credit: Hans Joosten

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Figure 1: Land degradation can be defined as the reduction in the capacity of the land to provide ecosystem services over a period of time. Pressures from land use can cause degradation. Soil carbon losses are an important form of degradation that can result in loss of productivity and of the ability to provide other ecosystem services. This map shows the status of land in regard to providing capacity for ecosystem services (low, high) and the direction of changes (strong degradation, weak degradation, stable, improving). These global results provide a first indication of pressures and trends at national and regional levels and allow for comparisons to be made between different land uses or geographical regions. Source: Nachtgerael et al. (2011)
Box 1: Soil organic matter and soil carbon

Soils are at the heart of the Earth’s “critical zone”, the thin outer veneer between the top of the tree canopy and the bottom of groundwater aquifers that humans rely on for most of their resources (US NRC 2001, PlanetEarth 2005). They form and continually change over thousands of years, at different rates and along different pathways, as mineral material from the breakdown of rock is colonized by plants and soil biota. This colonization leads to the formation of soil organic matter (SOM) and of soil structure, which controls carbon, nutrient and water cycling (Brantley 2010). Soil carbon exists in both organic and inorganic forms. Soil inorganic carbon is derived from bedrock or formed when CO₂ is trapped in mineral form (e.g. as calcium carbonate). Soil inorganic carbon is far less prone to loss than soil organic carbon (SOC). Although it can dissolve, particularly under acidic conditions, soil inorganic carbon is not susceptible to biodegradation.

SOC is the main constituent of SOM. SOM is formed by the biological, chemical and physical decay of organic materials that enter the soil system from sources above ground (e.g. leaf fall, crop residues, animal wastes and remains) or below ground (e.g. roots, soil biota). The elemental composition of SOM varies, with values in the order of 50 per cent carbon (Broadbent 1953), 40 per cent oxygen and 3 per cent nitrogen, as well as smaller amounts of phosphorus, potassium, calcium, magnesium and other elements as micronutrients. Soil biota (from microbes to earthworms) contribute living biomass to SOM mixing and breaking down the organic matter through physical and biochemical reactions. These biochemical reactions release carbon and nutrients back to the soil, and greenhouse gases such as carbon dioxide (CO₂), nitrous oxide (N₂O) and methane (CH₄) to the atmosphere (Figure 2).

Soil management can affect the relative balance of these processes and their environmental impacts. As SOM is broken down, some carbon is mineralized rather rapidly to CO₂ and is lost from the soil. SOM may also be lost through physical erosion. Organic nitrogen contained in biodegrading SOM is transformed to N₂O and other nitrogen oxide (NOₓ) compounds. However, some fractions of SOM are not readily degraded. SOC content therefore tends to increase as soil develops undisturbed over time. In water-saturated soils, SOM may even accumulate as thick layers of peat (Beer and Blodau 2007). Organic matter binds to minerals, particularly clay particles, a process that further protects carbon (Von Lützow et al. 2006). Organic matter also provides cohesive strength to soil and improves soil fertility, water movement, and resistance to erosion.

Figure 2: Soil-plant carbon interrelationships and associated ecosystem services. Soils, formed by the action of biota and infiltrating water and solutes on parent rock material, provide ecosystem services as flows of materials (sequestered carbon, water and solutes, plant nutrients, crop biomass) and information encoded in the genetics of soil organisms.
Carbon storage and other vital soil ecosystem services

Scientists have characterized many thousands of different soils. Each has a distinctive composition of minerals, living organisms, organic matter, water and gases (WRB 2006, FAO et al. 2009). Soils are formed over thousands of years as rock is broken down and colonized by plants and soil biota, leading to the formation of soil organic matter (SOM). While SOM is primarily carbon, it also contains nutrients essential for plant growth such as nitrogen, phosphorus, sulphur and micronutrients (Box 1). Organisms in the soil food web decompose SOM and make these nutrients available (Brussaard et al. 2007). The rate of SOM decomposition and turnover mainly depends upon the interplay between soil biota, temperature, moisture and a soil’s chemical and physical composition (Taylor et al. 2009).

Soils’ use and value are commonly associated with agriculture, but they are also of basic importance to the provision of many other ecosystem services (Box 2). The amount and dynamics of soil carbon are major determinants of the quantity and quality of these services. Ecosystem services are generally divided into four categories:

- **Supporting services:** These services underpin the delivery of all other services and the benefits that humans obtain from the natural environment. Soil organic matter is a key attribute which influences soils’ capacity to support ecosystem services. The inherent characteristics of soils (e.g. soil fertility, soil biodiversity, the capacity to capture, retain and transport water or carbon or to form and release greenhouse gases) are largely determined by the ability of different soils to form and break down soil organic matter.

- **Regulating services:** Globally, about 75 billion tonnes of soil per year is removed by wind and water erosion (Wachs and Thibault 2009). SOM promotes resistance to erosion of soils and helps regulate flooding by increasing infiltration, reducing runoff and slowing water movement from upland to lowland areas. It also reduces releases of agrochemicals, pathogens and contaminants to the environment by aiding their retention and decomposition (Burauel and Baßmann 2005). Soils have an essential role in climate regulation since soil carbon is the terrestrial biosphere’s largest carbon reservoir (Batjes and Sombroek 1997).

- **Provisioning services:** Soils are the basis of food and fibre production and are of vital importance to recharging water supplies. SOM is necessary to both these services because it influences nutrient and water availability and soil structure. It also increases resilience to climate change by helping protect plants and the environment against water stress and excess water. Carbon-rich peat soils have been a source of fuel throughout history. Today they provide growing media for gardeners, horticulturists and industry.

- **Cultural services:** From ancient times, human cultures have been strongly affected by the ways they use and manage soils. The character and carbon content of these soils have influenced the nature of landscapes and the environments in which diverse cultures have developed and thrived. SOM also helps soils to retain traces of past cultures and climates and to preserve archaeological remains.

Water infiltration is reduced in degraded soils. Therefore, in such soils less rainfall infiltrates to recharge soil and groundwater and more is lost to evaporation and runoff. Credit: Elke Noellemeyer

Water-saturated peatlands can conserve archaeological remains virtually forever. The mummified body of the Tollund Man, who lived 2 500 years ago, was found in 1950 in a peat bog in Denmark. Credit: Cochyn
Managing soil carbon for multiple benefits is key to its sustainable use. Trade-offs among the benefits that ecosystem services provide arise when soil management is focused on a single ecosystem service. For instance, using drained peatlands for biomass production greatly diminishes soil carbon stocks, degrades native habitats and alters the peatlands’ capacity to provide climate-regulating services. In contrast, soil carbon can be managed to enhance a range of ecosystem services. Increasing the SOM of degraded soils can simultaneously boost agricultural productivity, sequester CO2 whose emissions might otherwise exacerbate climate change, and enhance water capture.

What determines the global distribution of soil carbon?

The worldwide distribution of SOC reflects rainfall distribution, with greater accumulations of carbon in more humid areas (Figure 3). Most SOC is found in the northern hemisphere, which contains more land mass in humid climates than the southern hemisphere. Temperature plays a secondary role in global SOC distribution. This is illustrated by the occurrence of deep peat deposits in both tropical and polar humid areas.

Within climatic zones the amount of SOC is determined by soil moisture, which in turn is influenced by relief, soil texture and clay type. High soil water content tends to conserve SOM because reduced oxygen availability in wet soils slows the decomposition of SOM by soil microbes. Drier and well-aerated soils promote more rapid decomposition and accumulate less SOM. Where soil oxygen, soil moisture levels and nutrient status are sufficient, higher temperatures accelerate biological processes such as biomass production and decomposition, and therefore SOC dynamics (Batjes 2011). That is why draining peatlands provokes a rapid oxidation of stored SOM and releases large amounts of CO2 to the atmosphere, especially in warmer climates. Similarly, conversion of natural grasslands or forests to tilled soils breaks up soil aggregates, produces better aeration, and thus increases the decomposition of SOM and releases of CO2, with higher rates occurring in warm climates. Scientists have shown that in arable agriculture “no-till” land management reduces carbon losses and enhances the potential for carbon sequestration (Box 3).

The carbon content of soils under different land cover types varies substantially (Figure 4). The soils of savannahs are relatively low in SOC, but the carbon stocks of savannah soils are significant globally due to the large land area covered by this biome. In contrast, peatlands cover only 3 per cent of the global land area but contain almost one-third of global soil carbon, making them the most space-effective carbon store among all terrestrial ecosystems. Drained and degrading peatlands, which occupy 50 million ha worldwide (0.3 per cent of the global land area), produce more than 2 Gt of CO2 emissions annually – equivalent to 6 per cent of all global anthropogenic CO2 emissions (Joosten 2009).
Modelling, measuring and monitoring

Ways to estimate soil carbon stocks and fluxes at scales ranging from field to global continue to be developed (Bernoux et al. 2010, Hillier et al. 2011). The lack of adequate methodologies and approaches has been one of the main barriers to accounting for the significant mitigation effects that land management projects can have. This is important in the case of projects whose purpose is to sequester carbon in biomass or soils, or those that include sequestration as a co-benefit of reducing rural poverty or addressing food security. The Global Soil Mapping initiative will help provide a globally consistent set of soils data that are geographically continuous, scalable and include uncertainty estimates (Global Soil Mapping 2011). These data need to be

Box 3: Effects of no-tillage land management in Argentina and Brazil

In Argentina, which is currently experiencing agricultural expansion, no-tillage (“no-till”) land management has proven a viable alternative to conventional cultivation that involves working the soil with ploughs and harrows several times before seeding. Along with enhanced benefits from better water retention and infiltration and erosion prevention, small but significant increases in SOC stocks have been achieved where farmers changed to no-till systems (Alvarez and Steinbach 2009, Fernández et al. 2010).

In Brazil, changes in crop production practices have also had significant effects on soil carbon stocks. Conversion to no-till in soybean, maize and related crop rotation systems has resulted in a mean SOC sequestration rate of 0.41 tonnes per hectare per year. Pastures also have potential for soil carbon sequestration when integrated with arable agriculture (rotations), with the added benefit of increasing agricultural production (De Figueiredo and La Scala 2011, La Scala et al. 2011).

Figure 3: Organic soil carbon to a depth of 1 metre in tonnes per ha. Data are derived from the Harmonized World Soil Database v1.1. Source: UNEP-WCMC (2009)
Enhanced by contemporary field measurements (such as those supported in Africa by The Bill & Melinda Gates Foundation and the Africa Soil Information Service) and by progressive soil monitoring (Africa Soil Information Service 2011, Gates Foundation 2011).

There is also a critical need to develop universally agreed and reproducible field and laboratory methods for measuring, reporting and verifying (MRV) changes in soil carbon over time.

Box 4: The Carbon Benefits Project

Land use, land-use change and forestry (LULUCF) activities can provide a relatively cost-effective way to offset emissions through increasing removals of greenhouse gases from the atmosphere (e.g. by planting trees or managing forests) or through reducing emissions (e.g. by curbing deforestation) (UNFCCC 2012). However, it is often difficult to estimate greenhouse gas removals and emissions resulting from LULUCF activities. The UNEP-Global Environment Facility’s Carbon Benefits Project: Modelling, Measurement and Monitoring has developed a set of scientifically rigorous, cost-effective tools to establish the carbon benefits of sustainable land management interventions. These tools are designed to estimate and model carbon stocks and flows and greenhouse gas emissions under present and alternative management, and to measure and monitor carbon changes under specified land use (Figure 6).

An online toolset can be applied to projects involving soil services and natural resources management (e.g. forestry, agroforestry, agriculture and pasture management) in all climate zones. The modelling system enables projects to assess sources and sinks of CO₂ and other greenhouse gases at all points in a project cycle. The measurement system uses a combination of remotely sensed observations, ground calibration and web-enabled geographic information systems. It also provides estimates of CH₄ and N₂O dynamics based on direct field flux measurements.

Such approaches could allow for large area landscape assessments of above- and below-ground carbon for policy mechanisms whose purpose is to mitigate climate change through Reducing Emissions from Deforestation and forest Degradation (REDD) in developing countries. Greenhouse gas removals and emissions through afforestation and reforestation (A/R) since 1990 could be accounted for in meeting the Kyoto Protocol’s emission targets under certain rules (UNFCCC 2012). Parties could also select additional human-induced LULUCF activities, such as grazing land management, cropland management, forest management and revegetation, for which such tools could be useful.

Carbon measurement is currently being debated at several levels to correctly address carbon markets, for instance in the agricultural and forest sectors. Improved estimations of SOM, carbon stocks and fluxes could greatly help scientists to monitor and predict ecosystems’ response to climate change, as well as aiding policy makers when they take land use and management decisions and assisting land managers to gain better access to carbon markets.
The benefits of soil carbon

The vulnerability of soil carbon stocks to human activities

Soil carbon stocks are highly vulnerable to human activities. They decrease significantly (and often rapidly) in response to changes in land cover and land use such as deforestation, urban development and increased tillage, and as a result of unsustainable agricultural and forestry practices. SOC may also be increased (although much more slowly) by afforestation and other activities that decrease the breakdown of SOM (e.g. minimum tillage, perennial pastures, designation of protected areas). Practices that add more organic matter to the soil, such as composting or adding manure, may only improve the carbon balance of one site while diminishing that of another. Climate change is expected to have significant impacts on soil carbon dynamics (Schils et al. 2008, Conant et al. 2011). Rising atmospheric CO₂ levels could increase biomass production and inputs of organic materials into soils. However, increasing temperatures could reduce SOC by accelerating the microbial decomposition and oxidation of SOM, especially in thawing permafrost soils. Experts are concerned that if permafrost thaws, enormous amounts of carbon might be released into the air, greatly intensifying global warming (Schuur and Abbott 2011). Although the magnitude of this effect remains highly uncertain, recent estimates of frozen soil carbon are huge. According to some scientists, some 18.8 million km² of northern soils hold about 1700 billion tonnes of organic carbon (Tarnocai et al. 2009).

Current scientific knowledge of how local soil properties and climatic conditions affect soil carbon stock changes and carbon fluxes is insufficient and conflicting (Tuomi et al. 2008, Conant et

Permafrost thaws could result in releases of enormous amounts of carbon to the air. Credit: Hans Joosten

Figure 5: The effect of market prices on the efficacy of management measures to increase soil carbon. Source: Adapted from Smith et al. (2007)

Figure 6: The concept behind the Carbon Benefits Project online toolset. Source: CBP (2012)
Current use of drained peatlands on only 0.3 per cent of the Earth's surface is responsible for a disproportionate 6 per cent of global human-generated CO₂ emissions (Joosten 2009). Drained peatlands are increasingly used to produce biomass fuels such as palm oil in southeast Asia, sugarcane in Florida, maize and miscanthus in temperate Europe, and wood in parts of Scandinavia. This type of cultivation causes much greater CO₂ emissions than those saved by replacing fossil fuels with these biomass fuels (Couwenberg 2007, Sarkkola 2008, Wicke et al. 2008, Couwenberg et al. 2010).

Intensive land uses are also expanding into areas where SOC stocks are less resilient or soil conditions are marginal for agriculture. For example, semi-arid savannas and grasslands, tropical rainforests and peatlands are all being converted to arable land at an increasing rate. While temperate humid grasslands lose about 30 per cent of their SOC after 60 years of cultivation (Tiessen and Stewart 1983), soil carbon stocks in semi-arid environments can decrease by 30 per cent in less than five years when native vegetation or pastures are converted to cropland (Zach et al. 2006, Noellemeyer et al. 2008). Pastures established on cleared Amazon rainforest emit between 8 and 12 tonnes of carbon per hectare (Fearnside and Barbosa 1998, Cerri et al. 2007). Cultivation of tropical forest soils causes losses...
of more than 60 per cent of original SOC stocks in just a few years (Brown and Lugo 1990).

Tropical peatlands converted to cropland or plantations are another hotspot for carbon emissions (Box 5). Draining peat soils to introduce commercial production systems in tropical environments causes ongoing losses of up to 25 tonnes of carbon per hectare per year (Jauhiainen et al. 2011), while in boreal peatlands emissions from cropland are around 7 tonnes per hectare per year (Couwenberg 2011).

Consequences of soil carbon loss and the potential for soil carbon gain

Soil carbon losses not only result in higher atmospheric CO$_2$ concentrations through accelerated soil carbon oxidation, but also in a general loss of soil functioning and soil biodiversity. Less SOM, leads to decreased cohesion between soil particles, which increases the susceptibility of soil to water or wind erosion, accelerates losses of bulk soil, and alters nutrient and water cycling. Degradation of soil structure reduces the soil volume for water storage and soil permeability for drainage. In turn, this can lead to greater volumes of overland flow, which exacerbates flooding and reduces groundwater recharge during rain events. Reduced groundwater recharge aggravates water shortages and drought conditions. Another consequence of soil carbon loss is the loss of soil nutrients. These include nutrient elements within the SOM, as well as inorganic nutrients such as phosphorus and potassium that bind to mineral surfaces. Because of SOM’s role in forming aggregates, loss of SOM can reduce soil cohesion and allow the breakup of these aggregates (Malamoud et al. 2009). This increases the potential to lose bound clays and other minerals, either through bulk erosion or through colloid transport as water percolates through the soil profile.

In view of the many benefits of soil carbon, priority should be given to maintaining SOC levels in soils and, wherever possible, increasing these levels. Soil carbon gains can be achieved in two ways: first, by applying management strategies (including “set-aside” of land where this is socially and economically feasible) and technologies that reduce losses of existing soil carbon (this is particularly important in the case of dryland soils and natural grasslands or savannahs); and second, by applying sustainable management techniques that increase the levels of carbon in soils, particularly degraded agricultural soils (Box 6).

SOC losses can be reduced by minimizing oxidation of SOC in the soil profile and by reducing soil removal (e.g. removal of peat for fuel or horticultural use, or of soil for construction). In the case of mineral soils, which are typical of major cropping regions, reducing tillage can minimize soil carbon losses. In addition, carbon in the soil surface can be protected through practices that control erosion, such as shelter belts, contour cultivation and cover crops. In peat soils the naturally high carbon density can be preserved by maintaining wet saturated conditions, rather than by draining the peatlands to accommodate forestry or cropping such as oil palm plantations. In already degraded peat soils, raising water levels through drain-blocking can reduce further oxidation and contribute to maintaining and restoring carbon levels (Tanneberger and Wichtmann 2011). However, care should be taken not to inundate labile organic matter, such as fresh crop residues, since waterlogged conditions can lead to anaerobic decomposition that can produce large amounts of methane (CH$_4$), a potent greenhouse gas (Couwenberg et al. 2011).

Increasing SOC levels, on the other hand, can be achieved by increasing carbon inputs to soils. In the case of managed soils, this can be done by increasing the input and retention of aboveground biomass. Plants also allocate a significant portion of carbon below ground via their roots. This supports the soil biota in the rooting zone and, in turn, facilitates plant nutrient uptake, resulting in improved crop productivity and further increasing flows of carbon into the soil. Thus, sustainable land management for enhanced SOC levels is based on: optimal plant productivity (crop selection, appropriate soil nutrient management, irrigation); minimal losses of organic matter in soil (reduced tillage, erosion control, cover crops); and high carbon returns to the soil (i.e. leaving post-harvest crop residues or importing organic matter such as animal manures, biochar and domestic or industrial wastes, after consideration of the potential risks associated with using these materials).
Box 6: Strategies for maintaining and increasing carbon stocks in three major land use systems

Carbon stocks can be enhanced by ensuring that carbon inputs to the soil are greater than carbon losses from the soil. Different strategies are required to achieve this objective, depending on land use, soil properties, climate and land area.

Grasslands
The improvement of soil carbon in grasslands offers a global greenhouse gas mitigation potential of 810 Mt of CO₂ (in the period up to 2030), almost all of which would be sequestered in the soil (Conant et al. 2001, Ravindranath and Ostwald 2008). Overstocking of grazing animals can lead to the degradation of grasslands, increased soil erosion, depletion of SOC and increased soil greenhouse gas emissions. It should therefore be avoided. Activities that improve soil carbon in grasslands may include the following:

- Adding manures and fertilizers can have a direct impact on SOC levels through the added organic material and indirect impacts though increasing plant productivity and stimulating soil biodiversity (e.g. with earthworms that help degrade and mix the organic material). Fertilizer use can, however, result in N₂O emissions.
- Revegetation, especially using improved pasture species and legumes, can increase productivity, resulting in more plant litter and underground biomass, which can augment the SOC stock.
- Irrigation and water management can improve plant productivity and the production of SOM. These gains, however, should be set against any greenhouse gas emissions associated with energy used for irrigation, nutrient leaching affecting water quality, and the risks of evaporative salt deposits adversely impacting soil fertility.

Croplands
Techniques for increasing SOC in the agricultural sector include the following (Altieri 1995):

- Mulching can add organic matter. If crop residues are used, mulching also prevents carbon losses from the system. However, in flooded soils mulching can increase CH₄ emissions.
- Reduced or no tillage avoids the accelerated decomposition of organic matter and depletion of soil carbon that occur with intensive tillage (ploughing). Reduced tillage also prevents the break-up of soil aggregates that protect carbon.
- Judicious use of animal manure or chemical fertilizers can increase plant productivity and thus SOC, although adding excess nutrients can also increase losses of SOC as greenhouse gas emissions. All fertilizer additions must also consider the greenhouse gas costs of production and transport set against higher crop yields, which may offset demands for production on marginal land and farm-to-market transport.
- Rotations of cash crops with perennial pastures, and (in certain climates and farming systems) the use of cover crops and green manures have the potential to increase biomass returned to the soil and can therefore increase soil carbon stocks.
- Using improved crop varieties can increase productivity above and below ground, as well as increasing crop residues, thereby enhancing SOC.
- Site-specific agricultural management can reduce the risk of crop failure and thus improve an area’s overall productivity, improving carbon stocks.
- Integration of several crops in a field at the same time can increase organic material, soil biodiversity and soil health, as well as increasing food production, particularly for subsistence farmers.

Forested lands and tree crops
Forests have considerable potential to reduce greenhouse gas emissions to the atmosphere by storing large stocks of carbon both above and below ground. Strategies for realizing this potential include:

- Protection of existing forests will preserve current soil carbon stocks.
- Reforesting degraded lands and increasing tree density in degraded forests increase biomass density, and therefore carbon density, above and below ground.
- Trees in croplands (agroforestry) and orchards can store carbon above and below ground and even reduce fossil fuel emissions if they are grown as a renewable source of firewood.
In all cases, the success of strategies to increase soil carbon stocks will depend on the intrinsic capacity of a particular soil (e.g. mineral composition, clay content) and local soil formation conditions (e.g. climate, slope) as well as the nature of land use and management. To ensure that net SOC changes are real, greater emphasis needs to be placed on the assessment of SOC to depth alongside greenhouse gas emissions. Research is also needed to characterize the intrinsic SOC holding capacity of different soils in order to better target investment in management practices – that is, to compare current baseline SOC stocks and fluxes against potential ones under alternative management.

**The way forward: managing soil carbon for multiple benefits**

The world is experiencing rapid and unprecedented changes in land use, driven by increasing demand for food, water, energy and space for living (Verburg et al. 2011). Historically, the demand for food and fibre has been met by converting natural and semi-natural habitats to cropland in order to cultivate fertile soils with significant soil carbon stocks. As this demand grows in the future, cropping intensity will need to increase as less land becomes available for conversion to agriculture (Bruinsma 2003). Such land conversions have major implications for soil carbon stocks (Smith et al. 2010).

If current trends continue, there will be rapid losses of soil carbon to the atmosphere in years to come – not only exacerbating climate change, but also increasing the extent of global soil degradation and diminishing a wide range of vital ecosystem services. The consequences of further losses of soil carbon may take several decades to become obvious, by which time they could be difficult or expensive to address.

Soil carbon stocks vanish rapidly as a result of land use change and unsustainable management, while replenishing them is slow and requires significant investment. Positive actions can be taken now to avoid SOC losses by protecting soil carbon stocks and promoting sustainable practices that enhance SOC. Comprehensive accounting of social, economic and environmental costs and benefits can help ensure wide understanding of the local to global implications of land use and management changes that will maintain, enhance or degrade SOC.

Opportunities exist at the global, regional and local levels to enhance soil carbon and avoid losses of this resource. The challenge is to develop and implement planning processes, policies and incentive mechanisms that balance pressures on the soil from contrasting and (at times) conflicting demands for food, fibre and fuel crops, climate regulation, water, biodiversity conservation, living space and other benefits. In some locations, mechanisms will be needed to protect soils that are important soil carbon stores, such as peatlands and tundra, as an alternative to other uses such as agricultural or forestry expansion. However, in many cases multiple economic, societal and environmental benefits can be obtained on the same land through effective management of soil carbon.

There are examples worldwide of how multiple benefits can be derived through effective soil carbon management (UNEP-WCMC 2008, Marks et al. 2009, Kapos et al. 2010, Reed et al. 2010, Watson 2010). For instance, The World Bank’s BioCarbon Fund is providing the Kenya Agricultural Carbon Project with US$350 000 to pay smallholder farmers to improve their agricultural practices, in order to increase both food security and soil carbon sequestration (World Bank 2010). In parallel, the Great Green Wall initiative is a massive afforestation project to create a 15 km wide strip of trees and other vegetation along a 7 000 km transect of the African continent from Senegal to Djibouti (Bellefontaine et al. 2011). The objectives of this project include carbon sequestration, stabilization of soils, conservation of soil moisture and support for agriculture. Similar approaches are being monitored in China to assess whether they can sustainably reverse land degradation in arid regions (Bai and Dent 2009).

Proven technologies and management options are available for SOC conservation and enhancement, but whether they can be widely applied will be determined by the policies and incentives that encourage their use. Currently, the value of soil carbon (and soils in general) is rarely considered across sectors. The perceived benefits of soil carbon often reflect only the primary demands of a particular land use such as food production. In some parts of the world, land management strategies and policies are already...
in place to balance production pressures against other societal goals such as enhancing biodiversity or improving water quality. However, none were designed specifically to optimize soil management for multiple carbon benefits and associated ecosystem services. For instance, organic inputs to agricultural soils are generally targeted at increasing soil fertility, although this practice can also reduce soil erosion, achieve soil carbon sequestration and add resilience to farming systems.

There is a clear opportunity to use existing mechanisms, individually and in combination, to encourage active management of soil carbon and therefore expand the range of potential benefits. Where strategies to apply such mechanisms do not exist, there is an opportunity to design new strategies that take into account the multiple benefits of soil carbon management. Various global efforts and policy options exist that could be augmented to achieve wider benefits from SOC gains (Box 7).

Ultimately, these global agreements and policies could be linked in ways that encourage delivery of multiple benefits from soil carbon. In September 2011, the Food and Agriculture Organization of the United Nations (FAO) began planning with other UN agencies, including UNEP, for the establishment of a Global Soil Partnership to support and facilitate joint efforts towards sustainable management of soil resources for food security and for climate change adaptation and mitigation (FAO 2012). National and local regulations and incentives can also be used to promote improved soil carbon management for multiple benefits, with respect to existing land uses as well as restoration of degraded soils.

**Box 7: Global policy options to achieve soil carbon benefits**

- International climate change efforts to reduce the intensity of global warming (e.g. the United Nations Framework Convention on Climate Change) could indirectly reduce soil carbon losses by halting the acceleration of SOC losses in highly organic soils of the tundra and elsewhere, precluding the expansion of intensified land use in areas where current climatic conditions limit cultivation, such as mountainous regions, and promoting SOC gains in agricultural soils.

- Actions to address land degradation (e.g. under the United Nations Convention to Combat Desertification) could reduce carbon losses by encouraging soil conservation measures to prevent soil erosion and increase carbon stocks in affected areas, as well as by promoting practices that enhance soil organic matter (SOM) to restore degraded soils.

- Trade policies (e.g. through the World Trade Organization) could promote the market benefits from increasing soil carbon (e.g. through better prices for products derived from sustainable, carbon-friendly production systems identified by labelling) or counter losses of soil carbon from the expansion of particular land uses or crop types into vulnerable areas (e.g. through controls on the marketing of products that come from drained peatlands or the conversion of tropical rainforest).

- Global agreements could include tradable carbon or other credits (e.g. “green water”) for soils as a mechanism to manage soil resources in order to obtain environmental, social and economic benefits both on- and off-site (Tanneberger and Wichtmann 2011). Widespread adoption of soil organic carbon (SOC) management strategies will be influenced by the stability and level of the market price for SOC, as well as by access to financial mechanisms and incentives and by local issues such as land tenure. Carbon credits will only be effective if SOC sequestration can be adequately monitored and evaluated, and if long-term social and environmental impacts are adequately considered alongside short-term economic benefits.

- Conservation policies whose purpose is to halt biodiversity loss and protect ecosystems can also protect soil carbon stocks (e.g. when peatlands are rewetted or above-ground vegetation is restored) (Bain et al. 2011). The Convention on Biological Diversity and the Ramsar Convention on Wetlands focus on the protection and conservation of designated areas. An international mechanism to protect the world’s soil heritage exists under the World Heritage Convention. Its implementation would serve to improve the protection and management of soil resources, including soil carbon.
Such mechanisms could include:

- Land use planning that excludes vulnerable soils from land uses that lead to SOC losses.
- Promotion of management to protect and enhance SOM as an essential element of good soil and environmental quality.
- Regulations and guidelines on limiting emissions of greenhouse gases to the atmosphere, releases of soil carbon, nitrate and other contaminants to surface and groundwater, and drainage of carbon-rich soils.
- Promotion of sources of plant nutrients (e.g. cover crops, legumes, plant growth-promoting “bio-effectors”) that enhance SOC stocks.
- Financial incentives such as payments for carbon storage, flood control, improvement of water quality, conservation of soil biodiversity and other ecosystem services.
- Technical advisory systems (extension services) for agriculture and forestry that address the full range of ecosystem services that are supported by soils.

Soil carbon is easily lost but difficult to rebuild. Because it is central to agricultural productivity, climate stabilization and other vital ecosystem services, creating policy incentives around the sustainable management of soil carbon could deliver numerous short- and long-term benefits. Such policy incentives would need to target better allocation of soil resources to different land uses and management practices than has been the case under current policies targeted at supplying individual ecosystem services. Carefully crafted integrated policies could also avoid creating financial incentives that establish new conflicts or trade-offs involving soil carbon.

A new focus at all levels of governance on managing soils for multiple benefits by managing soil carbon effectively would constitute a significant step towards meeting the need for ecosystem services to support the world population in 2030 and beyond.

The aquatic warbler (Acrocephalus paludicola) is globally threatened and survives only in harvested, carbon rich wetlands. Credit: Franziska Tanneberger


