MANAGING SOIL ORGANIC CARBON FOR GLOBAL BENEFITS

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Managing Soil Organic Carbon for Global Benefits
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ACKNOWLEDGEMENTS

The authors are grateful to Michael Stocking, Annette Cowie, Mohamed Bakarr, Guadalupe Durón, Thomas Hammond, and the participants at the GEF-STAP workshop on "Soil Organic Carbon for Global Benefits: a Scoping Workshop for the Global Environment Facility" in 2012 for their valuable comments, and strong support for this work. We also thank Johannes Lehmann (Cornell University), Sabine Grunwald (University of Florida), Bernard Vanlauwe (International Institute of Tropical Agriculture), Tapas Bhattacharaya (National Bureau of Soil Survey and Land Use Planning, India), Henk Bouwman (STAP), and Brian Huntley (STAP) for peer-reviewing and strengthening an earlier draft of this report. We also are also grateful to Francisna Fernando (McGill University, Montreal Canada) for helping to prepare the document for design and printing.

Editor: John Smith

Design and Layout: DE Design + Environment

Printing: Master Print, Inc.

Cover photo: Mwanaidi Rhamdani (orange shirt) works with Maria Mtele (green shirt) in an orange-fleshed sweet potato field in rural Tanzania

Photo: The Gates Foundation

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The contents of this publication are believed, at the time of publication, to reflect accurately the state of the science on management of soil organic carbon. Nevertheless, STAP accepts responsibility for any errors. This publication was prepared for the STAP by the authors, serving as independent experts. The views and positions contained herein do not necessarily reflect the views of their affiliated institutions.

CITATION

Govers, G., Merckx, R., Van Oost, K. and van Wesemael, B. (2013). 'Managing Soil Organic Carbon for Global Benefits: A STAP Technical Report'. Global Environment Facility, Washington, D.C.

ABOUT STAP

The Scientific and Technical Advisory Panel comprises eight expert advisors supported by a Secretariat, which are together responsible for connecting the Global Environment Facility to the most up to date, authoritative and globally representative science.

http://www.stapgef.org

FOREWORD

The Scientific and Technical Advisory Panel of the GEF (STAP) is pleased to publish "Managing Soil Organic Carbon for Global Benefits: A STAP Technical Report" in support of the Land Degradation Focal Area and its importance to the mission of the Global Environment Facility (GEF). The Land Degradation Focal Area of the GEF addresses desertification and deforestation through the promotion of sustainable land management in agriculture, rangelands, and managed forests.

The concept for this paper originated through STAP discussions on the importance of multi-focal approaches to the delivery of global environmental benefits. Terrestrial carbon features as a primary component is fundamental to several of GEF's focal areas. In particular, the relationship between sustainable land management, soil organic carbon, and human developmental benefits was highlighted as a significant entry point to delivering global benefits. At the same time, the GEF in its focal area strategies was encouraging renewed attention to soil health as a basis for sustaining agricultural production and delivering ecosystem services.

Recognizing the multiple benefits of soil carbon management, STAP hosted a technical workshop on "Soil Organic Carbon for Global Benefits: A Scoping Workshop for the Global Environment Facility" in September 2012, which brought together 48 international scientists. The main aim of this workshop was to identify the most important entry points for GEF investments and to see how the protection and enhancement of soil organic carbon could be supported through GEF projects. Four distinguished scientists based at the Catholic University of Leuven/Louvain, Belgium (both the Dutch and French-speaking parts) were commissioned by STAP to prepare this report, which reviews current scientific understanding of the factors affecting soil carbon, and its management, and summarizes the outcomes of the technical workshop including recommendations to the GEF.

This STAP Technical Paper demonstrates that sustainable land management has the potential to contribute to both food security and multiple global environmental outcomes. Through this paper, we present an approach for soil organic carbon management as a foundational basis for the delivery of global environmental benefits, an objective held in common by the Conventions supported by the GEF. This includes the protection of biodiversity (above and below-ground), resilience of ecosystems, climate change mitigation, sustainable land management, and protecting the environment from persistent organic pollutants.

Addressing both environmental and developmental benefits through integrated approaches will be vital to the GEF as it enters its sixth phase (2014-2018). Managing soil organic carbon is central to the further development of landscape-scale approaches that embrace the interactions (trade-offs and benefits) between multiple components in land use-systems. It embraces multi-scale approaches linking micro-processes in the soil with global chemical and water cycles. We believe that managing soil organic carbon offers the GEF a viable avenue to address multiple common objectives across Conventions and the post-2015 Development Agenda, while accounting for the complex interplay that exists between environmental sustainability, agricultural productivity, and food security.

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ABBREVIATIONS & ACRONYMS

BP	Before present
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
DOC	Dissolved organic carbon
GEF	Global Environment Facility
GEFSOC	Global Environment Facility project Soil Organic Carbon (modeling system)
I	Input
IPPC	Intergovernmental Panel on Climate Change
LULCF	Land use, land-use change and forestry
mg	Milligram
Mg	Megagram (1 Mg = 1 metric tonne)
MRT	Mean residence time
N	Nitrogen
N_{org}	Organic nitrogen
Pg C	Petagrams of carbon (1 Pg = 10^{15} grams = 1 gigatonne or 1 million tonnes)
POC	Particulate organic carbon
POPs	Persistent organic pollutants
P_{org}	Organic phosphorous
ppm	Parts per million
R	Respiration
SMN	Soil monitoring networks
SOC	Soil organic carbon
SOM	Soil organic matter
STAP	Scientific and Technical Advisory Panel of the Global Environment Facility
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

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EXECUTIVE SUMMARY

Managing Soil Organic Carbon for Global Benefits presents an overview of current technical and scientific knowledge of soil organic carbon (SOC). Such an overview is needed in order to understand how and why soil organic carbon management should be an important component of future strategy for the Global Environment Facility (GEF). SOC management may contribute to and/or be affected by progress toward the achievement of the GEF objectives. It has a vital role to play in regard to each of the GEF focal areas: Biodiversity, Climate Change, Land Degradation, International Waters, and Persistent Organic Pollutants (POPs). Links also exist between SOC management and the GEF's cross-cutting themes (Sustainable Forest Management, and Land Use, Land-Use Change and Forestry – LULUCF). More specifically, this publication shows how SOC management potentially supports two of the objectives of the GEF, namely:

(1) ***Sequestering carbon and reducing greenhouse gas emissions*** – The GEF supports developing countries in both sequestering carbon and reducing greenhouse gas emissions for climate change mitigation. This requires full consideration of SOC stocks; it also calls for the development of SOC management strategies that will allow these stocks to be maintained or increased;

(2) ***Food security*** – The GEF aims to increase global food security by investing in the development and implementation of sustainable land management practices. Improving soil health is a basic element of this strategy. Not only are healthy soils more productive from an agricultural point of view, but they also provide other key ecosystem services. Maintaining a healthy level of SOC is essential to overall soil health and is explicitly mentioned in GEF strategy documents.

Knowledge of SOC and SOC dynamics has grown considerably in recent years, driven by a number of current debates including on the potential of soils to contribute to climate change mitigation, ecological approaches to agriculture, and pro-poor agricultural development, among many others.

While this publication provides a thorough scientific underpinning of the topic, it is not intended to focus on all aspects of SOC dynamics in full detail. Rather, it highlights the elements that impinge on the role of SOC management in delivering global environmental benefits:

- *SOC and climatic impact* –The potential climatic impact of future variations in the global SOC pool is highly significant. Given the magnitude of the climate change expected in the 21st century, it is certain that interest in sound SOC management will continue to increase.
- *SOC, land use and human impact* – SOC stocks are responsive simultaneously to environmental change and to human impact. Many studies have shown that total SOC stocks are strongly affected by land use and land management; intensive commercial agriculture tends to reduce SOC stocks, whereas some systems of organic and ecological agriculture may increase these stocks. Significant changes may occur within a time span of several decades. This implies that the benefits of sound SOC management will be noticeable over similar timescales and

may, at least theoretically, be relevant to the mitigation of greenhouse gas emissions in the short to medium-term, as well as contributing to human livelihoods.

- *SOC management and uncertainty* – Important uncertainties are associated with estimates of SOC stocks and their historical and future changes. This has implications for how investments to increase SOC stocks are planned and monitored. Uncertainty will decrease over time as experience increases. Therefore, sound knowledge management and rigorous tracking and monitoring are required.

From this overview of SOC dynamics and how SOC management relates to the objectives of the GEF, we propose the following principles to guide development of the GEF's vision for SOC management that delivers multiple benefits globally and locally:

- SOC management requires an integrated, landscape scale approach, taking a systems view.
- SOC management needs to be adapted to local climate, soil and agricultural conditions.
- SOC is easier (and probably cheaper) to preserve than to restore.
- Improving crop yields and restoring soil fertility through judicious application of nutrients from chemical fertilizers, green manure, compost, amendments, ash, farmyard manure or a combination (together with integrated pest management and soil moisture conservation) are the principal processes leading toward sound SOC management.
- Organic matter is in demand for other uses such as firewood and charcoal; therefore, realistic goals for its use in agriculture should be established that can be achieved within the setting of resource-poor farming households.
- Since carbon sequestration can generate multiple benefits at a variety of scales and intensities, all of these benefits should be assessed in terms of adding value.
- Socio-economic conditions need to be assessed, as they will affect the success of projects involving SOC management and, more broadly, the impact of changes in land management.
- Account should be taken of the biophysical, socio-economic and institutional risks inherent in the environment where a project is located.
- Adequate project support systems need to be provided, for example, for implementation of tracking tools and incentive mechanisms.
- Where possible, novel, high-throughput monitoring techniques should be used, in combination with an appropriate modeling framework.

SOC monitoring could benefit from remote sensing techniques developed in recent years. However, increased knowledge has confirmed that SOC dynamics are difficult to assess and predict – not only because SOC is complex in itself, but also because the inter-relationships between SOC and its controls are complicated. Better knowledge can therefore rarely be directly translated into straightforward SOC management rules; rather, this knowledge contributes to understanding a complex system whose response is inherently difficult to predict, yet where multiple benefits can potentially be achieved.

Nevertheless, some areas of research on SOC warrant specific attention. An area of high priority is ***the response of SOC to climate change***. The main reason this is crucial is that major changes in the magnitude of the SOC reservoir could themselves have a potential impact on global climate. At the same time, changes in climate will affect the SOC size of the reservoir through changes in biomass production and decomposition rates of organic matter. The question is also important to evaluating the efficacy of SOC management strategies, as the baseline ("no management change") carbon levels may change in response to climate change over the same timescale and at a similar magnitude as the management effects that need to be assessed.

"Eugênico Menezes, rice farmer, stands in his rice field on a late afternoon." Photo: UN Multimedia © Martine Perret

A second research priority is ***further evaluation of the "saturation" concept***. The potential to store C in the soil may be inherently limited by physiochemical soil characteristics. There is evidence that treatments which include organic matter addition and fertilization can increase SOC levels beyond those of adjacent "native" ecosystems, although the dynamics are again complex. Determining whether and how a soil becomes under- or oversaturated with carbon will be important to development of effective SOC management strategies.

A third priority research area is ***how SOC monitoring may be improved in the future***. Direct sampling and measurement is often used, but this requires vast financial and labor resources to cover large areas and timescales. Indirect sensing and modeling approaches hold greater potential for widespread application, yet there are issues of accuracy to be resolved. Credible, certifiable reporting of SOC stocks is essential if SOC sequestration is to become a significant part of global mitigation efforts. A good basis for further progress is the existing GEFSOC modeling framework.

While there is a need to improve our understanding particularly in these priority areas so that our conceptual description of SOC dynamics will become more mechanistic, further developing scientific knowledge is not in itself a strategy that will automatically result in more effective SOC management strategies. Other issues that may hamper efficient SOC management in addition to lack of knowledge, such as local socio-economic context and inadequate project support systems, also need to be considered when developing strategies for SOC management. Overcoming these hurdles could allow improved SOC management strategies based on current scientific understanding to be implemented. Therefore, the GEF might also give attention to ***how, with the present state of knowledge, the implementation of optimal SOC management can be advanced in various agro-ecological systems.***

INTRODUCTION

This publication presents an overview of current knowledge of soil organic carbon (SOC) as this understanding is relevant to SOC management and, more specifically, within the context of the objectives of the Global Environment Facility (GEF). Two major objectives of the GEF are directly related to SOC management:

First, SOC is a very important component of the global carbon cycle, and the fate of SOC will have an important impact on the future global climate. The GEF supports developing countries in sequestering carbon and reducing greenhouse gas emissions through climate change mitigation. Sustainable land management contributes to both objectives. This will require full consideration of their SOC stocks; it also calls for the development of SOC management strategies that will allow these stocks to be maintained or even to increase.

Second, the GEF aims to increase global food security by investing in the development and implementation of sustainable land management practices. Improving soil health is a basic element of this strategy. Healthy soils are not only more productive from an agricultural point of view, but they also provide other key ecosystem services. Maintaining a healthy level of SOC is essential to maintain or improve soil health and is explicitly mentioned in GEF strategy documents (Bakarr, 2012).

Given that perspective, the authors have provided a thorough scientific underpinning for all the statements made but have not discussed the various aspects of SOC dynamics in full detail. In this way, it is hoped that readers will gain insight into the complex interdependencies that affect SOC dynamics. Furthermore, *Managing Soil Organic Carbon for Global Benefits* considers how to incorporate SOC management in the sustainable land management strategies that need to be developed in the near future, especially in the developing world.

This publication is based on a discussion paper (Govers *et al.*, 2013) prepared for "Soil Organic Carbon for Global Benefits: a Scoping Workshop for the Global Environment Facility", which was organized by the Scientific and Technical Advisory Panel (STAP) of the GEF. The workshop was held in Nairobi, Kenya, on 10-12 September 2012.[1]

Photo: UNEP © Lawrence Hislop

[1] Information about the workshop, including all documents and presentations, can be found at www.stapgef.org/?p=534.


Photo: iStockphoto © Oralleff


"Terraced fields, Bhutan" Photo: World Bank Photo Collection © Curt Carnemark

SPATIAL & TEMPORAL DIMENSIONS OF SOIL ORGANIC CARBON

SOIL ORGANIC CARBON IN THE GLOBAL CARBON CYCLE

The carbon cycle is essential for life on Earth. While photosynthesis by plants, algae and cyanobacteria is the key mechanism allowing life to capture the sun's energy, carbon dioxide (CO_2) respiration is the main mechanism through which autotrophs and heterotrophs use part of the stored energy to fuel their metabolism. Within the carbon cycle, the soil acts as a major reservoir. Although there is large uncertainty associated with estimating the mean soil carbon (C) content of a biome or soil taxonomic order (with coefficients of variation of the order of 65%), recent estimates for the global soil C reservoir converge (Jobbagy and Jackson, 2000; Hiederer and Köchyl, 2012). It is estimated that global soils contain between 1400 and 1600 petagrams (Pg) of carbon (1 Pg = 10^{15} g) in the upper meter, and that the next meter of soil contains an additional 500-1000 Pg C (**Table 1**). These estimates imply that the soil organic carbon pool is more than twice the size of the atmospheric carbon pool (ca. 800 Pg) and that it contains about three times the amount of carbon in vegetation (ca. 550 Pg C). The exchange of C between terrestrial and atmospheric reservoirs by photosynthesis and respiration is of the order of 120 Pg C per year in each direction (Houghton, 2003). The overall size of the soil C reservoir is therefore relatively large compared to these gross annual fluxes of C.

Table 1. Global soil organic carbon (SOC) estimates (Pg) in soils to a depth of 1 and 2 meters

SOURCE	0 - 1 M	0 - 2 M
Batjes (1996)	1462-1548	2376-2456
Kasting (1998)	1580	
Robert (2001)	1500	2456
Jobbagy and Jackson (2000)	1502	1993
Post *et al.* (1982)	1395	
Hiederer and Köchy (2012)	1417	

In a first approximation, the carbon stocks in a soil can be seen as the result of a balance between the carbon gain through organic inputs (*I*) and carbon loss, mainly through respiration (*R*). The carbon input is the sum of all organic carbon added to the soil per unit of time (usually a year). It consists of the carbon present in, for example, crop residues, roots that die off, and the organic carbon in manure. Microbial life decomposes the carbon compounds to extract chemical energy from them; under aerobic conditions this eventually results in CO_2 emissions to the atmosphere. Anaerobic decomposition of organic carbon compounds, which occurs in waterlogged soils but is energetically far less efficient and proceeds at much slower rates, results in methane (CH_4) emissions to the atmosphere. Keeping everything else constant, the amount of SOC microbially metabolized and decomposed will be proportional to the amount of carbon present in the soil. Hence, doubling the soil carbon stocks would result in a doubling of the respiration rate.

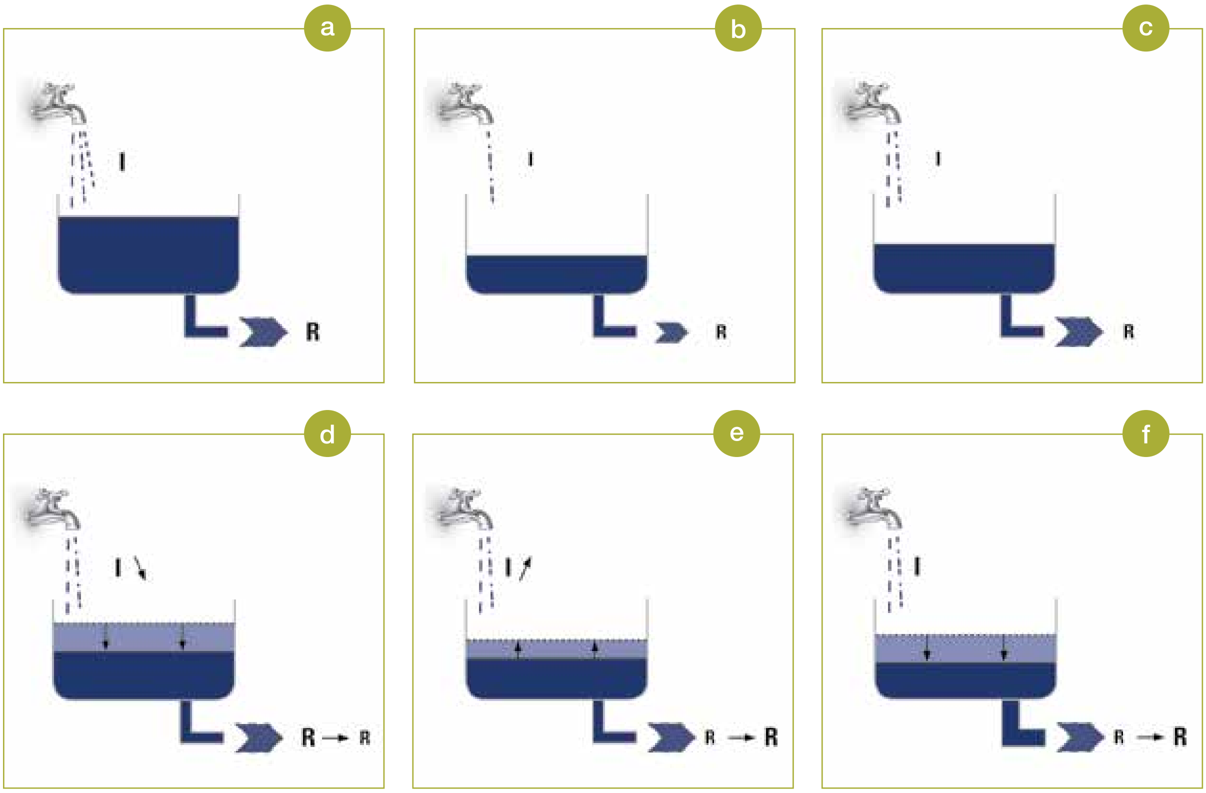

Figure 1. The kitchen sink as an analogy for SOC storage

Note: *The level of water in the sink is analogous to the total SOC inventory of a soil, while the tap discharge represents C input (I) and the drain discharge represents the C respiration rate (R). Panels a-c illustrate that different levels of equilibrium in SOC stocks (sink levels) are possible, depending on the amount of C input and C respiration (the drain discharge, R). Panels d-f illustrate the effect of changes in input or decomposition: if the input (tap discharge) decreases (e.g. due to crop residue removal), the level of water in the sink (C stocks) will become lower until the drain (respiration) rate is again equal to the new input rate (d). Similarly, if the C input rate (tap discharge, I) increases (e.g. due to enhanced vegetation growth caused by* CO_2 *fertilization), the level of the water in the sink (SOC stocks) will rise (e). Respiration rates may also change: higher temperatures and/or soil disturbance may lead to an increase in C respiration, in turn leading to a decrease in the SOC stocks (f).*

The amount of C in a soil is therefore the result of a balance between carbon input, which is essentially independent of the SOC stocks in the soil, and respiration, which will be proportional to the magnitude of the SOC stocks. An analogy is water level in a kitchen sink (**Figure 1**). The level of water (*the SOC stocks*) is determined both by the rate at which water is added (i.e. the discharge from the tap independent of the water level in the sink, or *the organic carbon input*) and the rate at which it flows away through the drain (controlled by the water level in the sink, *the C respiration rate*). The equilibrium stock of water results from the magnitude of the input (tap discharge) and that of the output (controlled by the diameter of the drain and the water level). As the output is dependent on the level of water in the sink, equilibrium will be reached at a certain water level. The ratio of outflow to total water volume in the sink determines the mean residence time (MRT) of the water. The MRT of SOC follows from a similar calculation:


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$$MRT = \frac{SOC}{R}$$

Where MRT = the mean residence time (in years), *SOC* = the total SOC stocks in the soil over a certain depth (kg C m^{-2}) and *R* = the respiration rate (kg C m^{-2} yr^{-1}). As respiration is assumed to be proportional to the total SOC stocks, this can be written as:

$$MRT = \frac{SOC}{k\ SOC}$$

Or:

$$MRT = \frac{1}{k}$$

Where k = the decomposition rate (yr^{-1}).

Barring human disturbance, the exchange between the soil reservoir and the atmosphere is globally in near-equilibrium: about 60 Pg of soil organic carbon is added annually to the soil reservoir through litterfall, throughfall, stemflow, crop residues and root turnover while a similar amount is lost through respiration of soil organisms, roots and mycorrizhae (Raich and Schlesinger, 1992; Houghton, 2007). A relatively minor amount of SOC (ca. 2 Pg, not accounted for in the kitchen sink analogy) is lost through the transport of dissolved organic carbon (DOC) and particulate organic carbon (POC) into rivers. A relatively large fraction of the DOC and POC (about 0.75 Pg) is decomposed in the aquatic system and released to the atmosphere, and the rest is transferred to the ocean reservoir or stored in sediments (Cole *et al.*, 2007). Further losses occur through fires (van der Werf *et al.*, 2010). These figures show that at least part of the soil carbon reservoir is relatively labile: 2-3% of all soil organic carbon is replaced annually, putting the MRT of the soil C reservoir that exchanges with the atmosphere at 30-50 years.

The soil C reservoir is not a single homogeneous reservoir, but a heterogeneous mixture of constituents of soil organic matter (SOM, i.e. the matter that contains organic C) in all stages of decay. As a result, the constituents of SOC – often referred to as carbon pools – have residence times which may vary from < 1 year for fresh leaves to > 10,000 years for very stable carbon components (Trumbore, 2000). There is general agreement that SOC dynamics can be functionally described using models that explicitly consider pools differing in residence times. For example, the RothC model subdivides SOM into "decomposable" and "resistant" plant material, microbial biomass, "humified" organic matter and "inert" organic matter with MRT's of 0.1, 0.3, 1.5, 50 and >10,000 years, respectively (Coleman and Jenkinson, 1999).

Explained in a very simplified way, the role of SOC in the global carbon cycle depends on the balance between changes in organic matter decomposition and organic matter input (as affected by climate, land use and management). If a rise in temperature would lead to an increased decomposition rate (i.e. the diameter of the drain increases) and a comparatively lower increase in primary productivity (the tap discharge increases, but less than the drain discharge), global SOC stocks may decrease (the water level in the sink decreases), contributing to further warming. If, on the other hand, primary productivity (and hence the input of organic carbon into the soil reservoir) increases faster than decomposition, the SOC stocks may rise and the soil may form a sink for atmospheric C. A recent meta-analysis confirmed that SOM is indeed responsive to global climate change. Globally, soil respiration rates have increased and this increase is correlated with (positive) temperature deviations (Bond-Lamberty and Thomson, 2010). While this may sound alarming at first, the analysis above shows that it does not imply that soils are a net source of C to the atmosphere, as the increase in respiration may well be a response to increased organic matter inputs and hence net increased SOC stocks in the soils.


Photo: iStockphoto © Ilbusca

The decomposition of organic matter should not be considered in isolation from primary productivity. They interact in multiple ways leading to different outcomes – depending, for example, on local soil conditions (Heimann and Reichstein, 2008). Nevertheless, manipulating the size of the soil C reservoir by increasing C inputs (e.g. through reforestation of cropland, improved efficiency of animal manure and crop residue use, conservation management) or decreasing SOM decomposition (e.g. through reduced tillage or no-till, improved forest management, set-aside of agricultural land) is at the heart of soil carbon sequestration. It should be stressed that soil respiration (and the associated SOC loss) is not bad *per se*. SOM decomposition is the inevitable consequence of active soil microbial life extracting its energy from the SOM. This microbial life is essential for plant growth and crop production, as it makes nutrients available for plant uptake. Thus, as Janzen (2006) put it: "(some of) the benefits of organic matter arise, not from its accumulation, but from its decay". Therefore, we need to develop strategies that maintain (healthy) respiration and, at the same time, allow the SOC reservoir to increase or at least be maintained at the current level.

SPATIAL DISTRIBUTION OF SOIL ORGANIC CARBON

The global distribution of soil organic carbon is spatially very uneven (**Figure 2**). Estimates of SOC stocks per unit surface area (also called SOC inventories, or SOC densities) by Jobbagy and Jackson (2000) and Tarnocai *et al*. (2009) up to a depth of 3.0 meters vary between 291 Mg C ha^{-1} for tropical forests and 91 Mg C ha^{-1} for boreal forests. Boreal peatlands have carbon densities far exceeding those of other soil types (> 1000 Mg C ha^{-1}). Croplands have, on average, a relatively low SOC density of ca. 177 Mg C ha^{-1} (Jobbagy and Jackson, 2000).

The distribution of SOC stocks is controlled by both natural and human factors. Soils can store large amounts of SOC when decomposition rates are very low (as in peatlands) or when primary productivity is high (as in tropical rainforests). Low SOC densities such as those in deserts/shrublands and croplands are explained by a low C input rate (due to low primary productivity or the removal of plant organic matter at harvest), a high SOM decomposition rate (e.g. due to a warm climate or soil disturbance) or a combination of both (Johnston *et al*., 2009).

There appears to be a relatively strong consensus on the total global magnitude of SOC stocks, but their distribution over different biomes (and hence corresponding carbon densities) is much less certain (**Table 2**). Eglin *et al*. (2010) illustrate this by comparing the estimates derived by Jobbagy and Jackson (2000) with those reported in a report published in 2000 by the Intergovernmental Panel on Climate Change (IPCC), based on estimates by the German Advisory Council on Global Change (WBGU) (IPCC, 2000a, b): the WBGU's estimate of SOC density under tropical forest was 723 Mg/ha as opposed to the 282 Mg/ha reported by Jobbagy and Jackson (2000). Variations for other biomes are similar in magnitude. This observation is important, as it implies that total global estimates – which are obtained by summing estimates for individual biomes – will be subject to relative uncertainty that is of at least the same order of magnitude as the relative uncertainty for estimates of individual biomes. Furthermore, the convergence of global estimates may partly be due to former estimates being reused in updated estimates. A recent, thorough discussion of the factors causing differences in global soil carbon estimations can be found in Hiederer and Köchyl (2012).

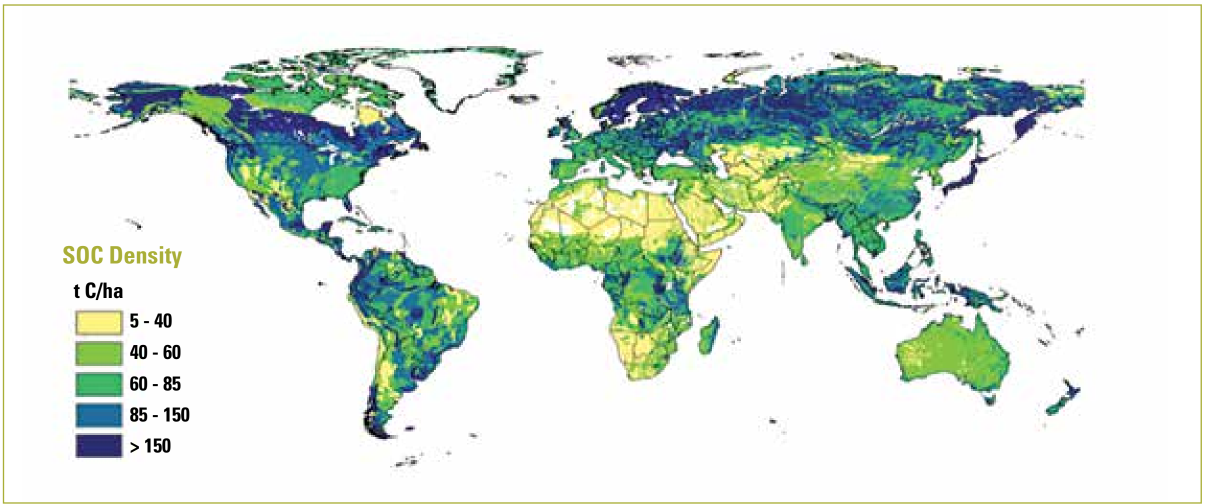


Figure 2. **Global variation in SOC densities at 0-1 meters in depth (Mg (megagram) C ha^{-1})**

Note 1: *Own processing based on data from the amended Harmonized World Soil Database (Hiederer and Köchyl, 2012; Panagos et al., 2012).*

Note 2: *1 Megagram (Mg) equals 1 million grams, which equals 1 metric tonne (t).*

Table 2. Total C stocks and C densities in different biomes

	AREA (10^{12} m^2)	SOC CONTENT (Mg C ha^{-1}) 0-1m	SOC CONTENT (Mg C ha^{-1}) 0-3m	SOC STORAGE (Pg) 0-1m	SOC STORAGE (Pg) 0-3m	UNCERTAINTY **
Boreal forest	12	93	125	112	150	
Crops	14	112	177	157	248	
Deserts	18	62	115	112	208	
Sclerophyllous shrubs	8.5	89	146	76	124	U
Temperate deciduous forest	7	174	228	122	160	
Temperate evergreen forest	5	145	204	73	102	
Temperate grassland	9	117	191	105	172	
Tropical deciduous forest	7.5	158	291	119	218	U
Tropical evergreen forest	17	186	279	316	474	U
Tropical savanna/grasslands	15	132	230	198	345	U
Tundra	8	142	180	114	144	U
Total of above	121			1502	2345	
Peatlands	3.5		1140-1430		400-500	U
Permafrost*	18.8		544		1024	U

Note 1: *Based on data from Jobbagy and Jackson (2000) and Tarnocai et al. (2009).*

Note 2: **Partly includes peatlands, boreal forests and boreal grasslands.*

***Assessments of stocks designated as U are particularly uncertain.*

PAST AND FUTURE CHANGES IN SOIL ORGANIC CARBON

Understanding the dynamics of the SOC reservoir at the global scale is critically important for assessing future climate change, especially in view of climate-carbon feedback. Progressive warming may lead to an overall increase in SOC respiration rates, thereby releasing additional CO_2 and exacerbating global warming (Jenkinson *et al.*, 1991; Davidson and Janssens, 2006). The human impact on the global SOC pool in the past appears to have been related mainly to land use change and, to a lesser extent, changes in land management. Conversion of forest and grassland to cropland has for the most part led to a strong and generally rapid (i.e. response times of less than 50 years) decrease in SOC stocks, which was first assessed by Houghton *et al*. (1983). A detailed overview of the experimental data available on the effects of land use change on SOC stocks was provided by Guo and Gifford (2002). They found an average reduction in SOC stocks of ca. 42% when land was converted from forest to cropland. The decrease was even greater when pasture was converted to cropland (59%). Changes in SOC stocks when land use change is in the opposite direction were also important, with an average increase of 53% when cropland was converted to secondary forest but only 19% on average when cropland was converted to pasture.

Although the magnitude of short-term (i.e. decades) changes in SOC stocks due to relatively recent land use change is relatively small, this is not the case for changes in SOC stocks over longer time spans (centuries to millennia). Ruddiman (2003) was the first to notice that, contrary to what has been observed for other interglacials, atmospheric CO_2 rose consistently from ca. 260 ppm to ca. 280 ppm between 8000 BP and 1000 BP, attributing this change to the impact of early deforestation releasing ca. 300 Pg C from soils to the atmosphere. However, this view is not generally accepted since the $\delta^{13}C$ record, as well as simulations of carbon dynamics over the entire Holocene, suggest that other mechanisms are responsible for the observed increase (Joos *et al*., 2004; Elsig *et al*., 2009). More recent estimates of the historical, pre-industrial release of SOC due to human land use changes are significantly lower than those of Ruddiman, although they still show a considerable range (48-114 Pg) (Pongratz *et al*., 2009).

It may appear more straightforward at first to assess the effects of comparatively recent land use change since a larger amount of historical data is available. Several studies have indeed attempted to assess the loss or gain in SOC over the last century or two. Using a spatially explicit model, Eglin *et al*. (2010) concluded that overall SOC stocks did not change much during the last century (1901-2000). Model simulations accounting for the effects of temperature, CO_2 fertilization and land use change resulted in an overall, non-significant decrease of ca. 7.3 Pg C in the global SOC stocks. If land use change was omitted, an increase of ca. 27 Pg was simulated, resulting in an overall gross land use effect of -34.3 Pg. Thus, the negative effects of land use change were more than compensated for by the positive effects of global warming and CO_2 fertilization. These results deviate from those of an earlier comparison study, where most models simulated a more important increase (up to 80 Pg C) of the SOC stocks between 1900 and 2000 (Friedlingstein *et al*., 2006). Eglin *et al*. (2010) attributed this deviation to their model setup allowing them to take properly into account the effect of land use and historical land use changes, a capacity that most of the models used by Friedlingstein *et al*. (2006) lacked.

Other studies focusing on the effects of land cover change (not considering the effects of climate change) result in estimates of C *releases* to the atmosphere of between 108 Pg and 188 Pg for the period 1850-2000 or 1850-1990 (Olofsson and Hickler, 2008; Strassmann *et al*., 2008; Pongratz *et al*., 2009): these losses, however, include losses from both vegetation and soil and are therefore larger than those obtained by Eglin *et al*. (2010) for SOC only. It should be kept in mind that, in the last decades, net SOC losses due to deforestation and agricultural intensification may have been reduced or even totally compensated for by recent afforestation, especially in temperate areas, which is not adequately captured by land use datasets (Kaplan *et al*., 2012).

Estimates of future changes in SOC stocks are even more uncertain. It is usually assumed that future changes in these stocks will be negative, and that additional releases of SOC to the atmosphere are to be expected. The reasoning is that the positive effects of increasing CO_2 levels on plant growth will reach a saturation point as other factors become limiting, thereby fundamentally limiting carbon inputs into the soil (Jenkinson *et al*., 1991). On the other hand, SOC decomposition rates may continue to rise with increasing soil temperatures, which could have particularly important implications for the stability of the large SOC pools in arctic zones, where SOC decomposition may be strongly stimulated by the strong temperature increase in this region (Schuur *et al*., 2009), possibly exacerbated by fertilization effects (Mack *et al*., 2004).[2] While there is reason for concern, our understanding of the basic mechanisms controlling SOC dynamics is still insufficient to make reliable estimates (Trumbore and Czimczik, 2008; Schmidt *et al*., 2011). In particular, the effects of rising temperatures on adsorbed SOC may be lower than expected (Davidson and Janssens, 2006).

Further progress in understanding how SOC responds to temperature change will require studies specifically designed to disentangle the various mechanisms that control the temperature response of different SOC pools (Conant *et al*., 2011). Conant *et al*. (2011) describe how various

[2] The Arctic contains nearly half of global soil carbon, but low temperatures suppress soil biota and retard the decomposition of organic matter. Although global warming may change the dynamics of Arctic stored carbon, it is difficult at this stage to predict outcomes (Sistla et al., 2013). (See also the paragraph on peatlands in Section 4, under "Climate Change".)

processes (depolymerization of SOC, [3] microbial enzyme production, adsorption-desorption) may control the overall response to temperature change. While it may be possible to identify the exact contribution of changes in various process rates in a controlled setting, predictive modeling based on such a mechanistic approach will be complicated by difficulties in parameterizing such a model in a real world setting. As more detailed environmental models have greater degrees of freedom and require more parameter values, their predictive application is invariably plagued by uncertainties with respect to determining the correct parameter values and to the final predictions (Beven and Binley, 1992; Govers, 2011). There are also uncertainties about how future climate change could change local soil conditions: a recent modeling study (Falloon *et al.*, 2011) showed that the magnitude and direction of the soil carbon-climate feedback may depend critically on the highly uncertain evolution of soil moisture, as water in the soil has a strong impact on SOM decomposition rates.

In regard to soil management, both positive and negative effects may be experienced. Improved drainage of waterlogged soils and peatlands contributes significantly to the release of C from the soil to the atmosphere (Bellamy *et al.*, 2005; van Wesemael *et al.*, 2010; Liu *et al.*, 2011). However, appropriate management of croplands may lead to significant increases in SOC (Ogle *et al.*, 2005; Sanderman *et al.*, 2010) even if this does not always appear to be the case (Manley *et al.*, 2005; Angers and Eriksen-Hamel, 2008).

This part of the analysis has not gone into any detail regarding the management of SOC for global environmental benefits. Nevertheless, some important conclusions may be drawn that have significant implications for SOC management.

First, SOC is not only important when looking at the environment from a soil quality perspective: the potential impact on the global climate of future variations in the global SOC pool is also highly significant. Given the magnitude of the climate change expected in the 21st century (STAP, 2012), it may safely be assumed that interest in sound SOC management will continue to rise.

Second, SOC stocks are responsive to environmental change and to human impact. Many studies have shown that total SOC stocks can be strongly affected by land use and land management. Significant changes occur within a time span of several decades, as can be expected from experimentally determined MRT's for SOC. This implies that the benefits of sound SOC management will be noticeable over similar timescales and may, at least theoretically, be relevant to the mitigation of greenhouse gas emissions (Lal, 2004). However, the response of any one SOC reservoir to an external forcing will show a considerable lag time (Poeplau *et al.*, 2011). Hence, collectively the various SOC reservoirs should be considered to be out of equilibrium in an era such as ours, during which diverse rapid changes are affecting soil organic carbon both directly and indirectly. This may have implications for SOC management and for evaluating the effectiveness of different management techniques (Sanderman *et al.*, 2010).

Finally, important uncertainties are associated with estimates of SOC stocks and their historical and future changes. These uncertainties are unlikely to be greatly reduced in the near future. Therefore, recommendations for SOC management will need to take them into account.

[3] Depolymerization is the process of converting a polymer (a large molecule composed of many subunits or monomers) into its component monomers such as amino acids, glucose and nucleotides

MAJOR ISSUES OF POTENTIAL RELEVANCE TO THE GEF

SUSTAINABLE AGRICULTURE AND FOOD SECURITY

Maintaining carbon stocks in soils is a traditional – while often neglected – management goal in regard to sustainable agriculture that will support food security. Achieving this goal can generate a large number of additional benefits pertaining not only to climate change mitigation, but also to biodiversity conservation and to ecosystem services that derive directly from the maintenance of natural ecosystems. While the maintenance of carbon stocks in soils only indirectly addresses the objectives of the GEF, the issue of its relation to sustainable agriculture is highly pertinent. Soils better endowed with stable SOM perform better in providing a large number of soil functions that are critical for crop production, including nutrient and pH buffering, water retention, soil structural stability, and higher agronomic efficiency with respect to fertilizer inputs (Vanlauwe *et al.*, 2011). Where the use of these often expensive inputs – which in some cases consume non-renewable resources (e.g. rock phosphorus deposits) – can be minimized, there is an ensuing positive impact on the environment. The link with the objectives of the GEF builds on the intrinsic connection between carbon stocks in soil and soil quality.

Maintaining carbon stocks and soil quality is closely linked to the maintenance of crop production levels on existing croplands. Meeting food demand in 2050 while minimizing environmental impacts will require a shift from the ever-intensifying agriculture in richer countries (with expected diminishing returns on investments) and greater land clearance in poorer countries toward moderately intensified agriculture in the "underyielding" countries (see, for example, Tilman *et al.*, 2011). The latter would be achieved through the transfer of high-yielding technologies (e.g. organic matter management, soil conservation, improved germplasm, fertilizers and crop protection), allowing farmers in these countries to continue farming the same amount of land with better returns.

This shift could be thought of as the introduction of "best practices" in tropical soil fertility management, or Integrated Soil Fertility Management as defined by Vanlauwe *et al.*, 2010. It inevitably implies a strong emphasis on SOC management. In addition to the obvious adverse effects, in terms of greenhouse gas (GHG) emissions, of land clearance (estimated at 1 billion ha globally between 2005 and 2050), the low efficiency of nitrogen use in over-intensified agriculture leads to excessive GHG emissions in the order of 3 Pg yr^{-1} (CO_2 equivalent [4]), whereas It is estimated that adopting the alternative path would reduce land clearance to some 0.2 billion ha over the same 45-year period and GHG emissions to about 1 Pg yr^{-1} (CO_2 equivalent) (Tilman *et al.*, 2011). It is important to emphasize the apparent contradiction that intensifying agriculture by increasing nitrogen fertilizer use in some areas leads to reduced environmental impact at a global scale. This points to the risk of imposing regulations and solutions that "work" in better endowed regions on areas in which food security remains a very important issue.

In short, while maintaining soil carbon stocks is a sensible management goal from the climate change perspective, it is crucial to reach food security in the long run. The use of organic matter management and inorganic fertilization, combining the best of two worlds, to reach the required level of staple food production in Africa illustrates this eloquently (Sanchez, 2010).

[4] CO_2 equivalent is a metric measure used to compare the emissions from various greenhouse gases based upon their global warming potential.

"Harvesting rice in east Java" Photo: Fao ©H.Null

THE DYNAMICS OF SOIL ORGANIC MATTER (SOM): A PERSISTENT RESEARCH AREA

Describing the dynamics of SOM has been a persistent research area in the last decades, previously triggered by its perceived impact on crop production – and indeed the literature abounds with examples of this (Lal, 2001) – but nowadays also spurred by concern about the role of terrestrial carbon stocks in the global carbon budget.

The Processes Controlling Soil Organic Matter are Not Fully Understood

The widely variable and heterogeneous composition of SOM and the difficulties in assessing its chemical structure have long hampered significant progress in this area. In that context, it is interesting to observe that traditional attempts to elucidate the chemical structure of SOM components (seemingly abandoned between the 1970s and 1990s in favor of the more tangible physical fractionation schemes) now seem to be making a comeback. This reversal has been made possible by the emergence of more sophisticated analytical tools such as NMR spectroscopy (e.g. Kiem *et al.*, 2000), which allow detailed observations without disturbing the intricate interactions between the organic and mineral components of the soil. However, despite significant progress in elucidating the chemical structure of SOM components (Kelleher and Simpson, 2006) and their distribution at a very fine scale (Lehmann *et al.*, 2008b), establishing direct links with their functionality and/or immediate predictions about their dynamics remains a challenge.

It has long been recognized that descriptions of the behavior of organic matter are made more easily when the entire SOM pool is separated into fractions which are more homogeneous and more similar in behavior in comparison to the entire pool (Six *et al.*, 1998). During soil formation an intricate process of decomposition and intimate mixing of SOM and mineral soil constituents occurs, so that understanding what controls the stability of organic components in a soil is complex. It is difficult to know whether it is the chemical structure of organic matter, the degree of association of organic matter with mineral surfaces of various types, the degree of pore filling and/or the degree of physical separation that render the organic material more or less accessible to the soil biota responsible for its degradation. Furthermore, these factors interact in two directions. While the chemical structure of SOM affects its association with mineral surfaces, the degree of physical protection will ultimately also affect the chemical structure of the soil organic carbon that is preserved.

The fractionation procedures currently used are based on density and/or size separation. These procedures result in SOM fractions with different compositions and/or responses, such as respiration rates after incubation (see, for example, Zimmermann *et al.*, 2007). This suggests that interaction with mineral components of the soil matrix over-rules the chemical characteristics of the SOM with respect to decomposability. Combining density and aggregate- and particle-size separation has been proven to isolate fractions of SOM that are relevant in a wide range of ecological contexts. Some fractions react to changes in management more readily than the bulk SOM (Elliott, 1986; Christensen, 2001; Six *et al.*, 2002). The most resistant plant-derived components are often found in the smallest size fractions, i.e. the clay and fine silt fraction, where they are strongly associated with soil minerals. This approach has had a significant impact on our understanding of how soil aggregate stability interacts with organic matter dynamics and how various management decisions affect soil carbon stocks.

There are recent trends to combine the above mentioned density/size separations with advanced spectroscopic techniques, as the different size fractions vary greatly in their characteristics depending on their origin and history. Pyrolysis-field ionization mass spectrometry, scanning transmission X-ray microscopy (STXM), Near Edge X-ray Absorption Fine Structure (NEXAFS), ^{13}C-NMR, mid-infrared spectroscopy (MIR), visible/near-infrared spectroscopy (VNIR) and nano-scale secondary ion mass spectrometry (nano-SIMS), among other techniques, are increasingly used to further elucidate the relationships between different carbon pools and their kinetic behavior (Lehmann *et al.*, 2005; Wan *et al.*, 2007; Kruse *et al.*, 2010; Gillespie *et al.*, 2011).

Some methods yield information on where the carbon resides in the soil matrix and in what form, i.e. as a coating or a discrete particle; others provide detailed information about elemental

“An Afghan Farmer plows land” Photo: UN Multimedia © Fardin Waezi

composition and the presence of functional groups (e.g. aromatic, aliphatic, carboxylic or phenolic). The main lesson emerging from recent work is that real progress can only be achieved through a combination of approaches, integrating structural chemistry with more conceptual or pragmatic approaches based on functional carbon pools. Ideally, experiments and monitoring should feed into a modeling framework that allows carrying out scenario analyses that predict soil carbon dynamics when there is climate change and/or changing land use. Promising indicators based on the combination of stable isotopes and conventional elemental analyses (Conen *et al.*, 2008a; Conen *et al.*, 2008b) or biochemical components such as lignin-derived phenols or suberin/cutin derived fatty acids (Crow *et al.*, 2009) have emerged over the last years.

A SOM fraction that has gained increasing attention in recent years is ***black carbon***, a residue of incomplete combustion of fossil fuels, wood and other biomass (Schmidt and Noack, 2000; UNEP and WHO, 2011). Black carbon is a ubiquitous component of soils (Skjemstad *et al.*, 2002; Krull *et al.*, 2008). Despite the comparatively small contribution of black carbon to the total C input into soils (Forbes *et al.*, 2006), soil organic matter is often enriched in black carbon due to its much lower decomposition rates (Lehmann *et al.*, 2008a). Knowing the proportion of this highly stable fraction of SOC can dramatically improve predictions of SOM losses due to soil cultivation (Skjemstad *et al.*, 2004) or as a response to global warming (Lehmann *et al.*, 2008a). Despite its slow turnover time, black carbon may play a role in enhancing soil fertility due to its greater ability than other SOM to retain cations (Liang *et al.*, 2006; Mao *et al.*, 2012).

An important issue related to SOC storage is whether ***carbon saturation of soils exists***. Such saturation would imply a threshold level of carbon in a given soil beyond which adding carbon would seem inefficient (Stewart *et al.*, 2008), thereby constraining SOC accrual in agricultural soils. Current knowledge points to the possibility of saturation of some SOM pools (i.e. the mineral associated one for obvious reasons, and other pools without a saturation limit) and, consequently, also much decreased stability. Not surprisingly, links between soil texture (Hassink, 1994) and even clay mineralogy (Denef *et al.*, 2004) and the potential to store carbon have been described in the past. The potential of a soil to store added carbon may not always be a linear function of the amount of soil organic carbon already present. It may also depend on the soil's structural status. Soils that have been under cultivation for extended periods may lose some of their potential to store carbon due to a lack of aggregation (Kimetu *et al.*, 2009).

Since SOM composition, level and distribution are the result of a combination of physico-chemical and biological processes, additional understanding may result from unraveling the different ***food webs*** that exist in soils. Attempts to assign the occurrence of a given component to, for example, specific types of vegetation, fungal versus bacterial decomposition pathways, and the importance of the role of specific soil invertebrates may benefit tremendously from recent advancements in compound specific stable isotope analysis combined with the tracing of specific bio-marker molecules. These new developments, which originated in organic geochemistry and were first mainly used for paleo-environmental purposes, have been eagerly adopted by ecologists to unravel hitherto inaccessible element pathways in the most diverse ecosystems (Boschker and Middelburg, 2002).

The importance of long-term field trials for understanding the dynamics of SOM has recently been emphasized by Peterson *et al.* (2012). This is an issue of major importance. Most long-term trials pertain to agriculture in temperate climates, whereas in tropical regions the dynamics remain largely unknown (Diels *et al.*, 2004). Together, differences in soil mineralogy, climate and types of organic matter inputs may lead to slightly or drastically different controls of SOM stability (Torn *et al.*, 1997), precluding a straightforward transfer of concepts generated basically from research on temperate systems.

Modeling Soil Organic Carbon: Limits To Predictability

SOM process studies will continue to greatly enhance understanding of the underlying chemical and biological processes and of the metabolism in the soil ecosystem. Yet while extremely rewarding scientifically, it remains unlikely that increased understanding of the precise mechanisms of SOC stabilization will lead in the short run to drastically improved predictive capacity. Equally, better knowledge of the mechanisms is unlikely to generate improved policy guidelines, reaching beyond what can already be achieved with the semi-empirical approach (based on size and density separates in combination with the SOM models) currently favored.

The key reason for this is that models based on such detailed processes are likely to be very difficult to implement at a temporal and spatial scale relevant to SOC management. While it may be possible, at least theoretically, to collect the detailed input data needed (e.g. SOC and microbial biomass composition, soil structure, soil moisture status), uncertainty would necessarily be associated with all the input data required: this would cause the data input error to increase with increasing model complexity (**Figure 3**). Furthermore, such a model would need values for a relatively large number of parameters, which would have to be determined empirically.

One of the main resulting problems is equifinality in predictions (i.e. similar predictions can be obtained using significantly different sets of parameter values) (Beven and Binley, 1992). Consequently, model predictions obtained from more complex models may be highly uncertain – especially when a model is applied outside the range for which it was calibrated – and models of intermediate complexity may outperform more complex models in terms of predictive capacity, as shown in **Figure 3** (Van Rompaey and Govers, 2002).

Enhanced understanding, resulting from a much better explanation of the true nature of the speciation of organic matter components in soil aggregates of diverse sizes, may not directly lead to an improved prediction of the response of SOC to

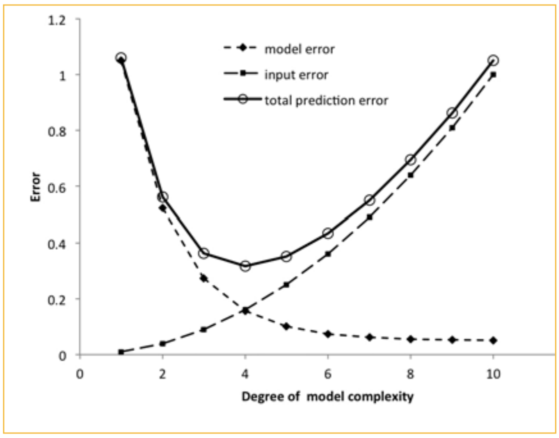


Figure 3. Errors in predictions are a function of both model error and input error

Note: *Model error (bias) will be greatest for a model of low complexity, as the model will be incapable of properly describing the various processes that control the phenomenon under study (e.g. the SOC stocks in a soil). Increasing the model complexity will reduce this model error. However, as the model gradually becomes more complex, the uncertainty of the input data needed to run the model as well as the uncertainty of the parameter values (here treated together as input error) will increase. Models of intermediate complexity therefore often outperform more complex model formulations in terms of predictive capabilities (Van Rompaey and Govers, 2002).*

changes in environmental drivers. However, it will be essential to provide the mechanistic rationale behind hitherto mainly conceptual approaches. In the longer term, this improved understanding may lead to the development of new model structures refining or replacing the box-modeling approach that is the current standard in the best-known models such as RothC (Coleman and Jenkinson, 1999) and CENTURY (Metherell *et al.*, 1993). Models based on a more detailed description of SOC dynamics as the SOC interacts with other soil constituents are currently being developed (e.g. Malamoud *et al.*, 2009). While the development of such models is a long-term goal, significant improvement in SOC dynamics modeling for large areas may already be achieved using models that allow accounting for different SOC pools rather than approaches based only on rough estimates for a given land use, soil type and climate. Such models could be further improved by explicitly accounting for factors known to be important but currently not considered, such as soil mineralogy (Torn *et al.*, 1997).

The Need For Soil Organic Carbon Monitoring

Lack of information makes a rational policy aimed at SOC maintenance difficult to implement for either soil quality or carbon sequestration purposes. Ways to obtain needed information include the development of tools to (i) assess carbon distribution in the soil profile, (ii) monitor the effectiveness of land management strategies in enhancing SOC accumulation and storage, and (iii) quantify the stability of the stored SOC. The last of these, in particular, has received considerable attention in recent years, and new approaches and indicators to quantify the stability of stored SOC are being developed (Conant *et al.*, 2011).

Information is especially needed at the landscape scale. Vertical carbon distribution and stability, as well as the effectiveness of management strategies, are spatially variable and need to be accounted for when considering SOC management. Thus, models are required that allow transferring the knowledge gained from detailed, process-based studies to the landscape scale. This is important not only because changes in SOC stocks and quality should be assessed at this scale, but also because landscape-scale modeling allows the most important controls on SOC dynamics to be identified. This information may feed back into process-based studies to ensure that the most relevant factors at the landscape scale are properly accounted for in SOC models.

Over the last decade, significant progress has been made in this area, with successful attempts to quantify not only total carbon stocks but also distinct carbon pools at the landscape level (Vasques *et al*l., 2010b; Meersmans *et al.*, 2011). In the future, such efforts could benefit significantly from the use of novel, non-destructive and rapid measurement techniques such as VNIR and MIR spectroscopy (Grandjean *et al.*, 2010), including their use on aircraft or satellites (Stevens *et al.*, 2008). [5]

[5] See also Section 5, under “SOC monitoring”.

“A farmer tends the fields in Decca” Photo: UN Multimedia

LINKAGES TO GEF FOCAL AREAS

This section addresses the role that SOC and SOC management could play in regard to each of the GEF focal areas: Biodiversity, Climate Change, Land Degradation, International Waters and Persistent Organic Pollutants (POPs), as defined in *GEF-5 Focal Area Strategies* (GEF, 2011). How SOC management might be considered with respect to GEF’s cross-cutting themes (Sustainable Forest Management; Land Use, Land-Use Change and Forestry – LULUCF) is also discussed.

BIODIVERSITY

Biodiversity loss not only results in losses of irreplaceable individual species, but also has implications for the functioning of ecosystems, threatening their robustness and putting the services they supply at risk. Loss of biodiversity leads to fundamental changes in ecosystems and negatively affects their overall performance (e.g. primary productivity) (Hooper *et al.*, 2012; Reich *et al.*, 2012). Given that extinction rates are at an all-time high and that a sixth extinction event is well under way (Barnosky *et al.*, 2011), biodiversity conservation is a matter of protecting not only individual species but also the world environment.

As this publication concentrates on SOC, soil biodiversity will be briefly discussed, followed by the linkages between the GEF Strategy for Biodiversity and SOC management. Soil biodiversity is largely imperceptible and is therefore often still neglected in biodiversity assessments (Wall *et al.*, 2010). Yet below-ground biodiversity is quantitatively (in terms of number of species) more important than above-ground biodiversity. While most species of soil biota have not been described, the major groups (bacteria, fungi, nematodes and insects) together contain at least several hundreds of thousands and possibly millions of species (De Deyn and Van der Putten, 2005). Available evidence also demonstrates close linkages between below-ground and above-ground biodiversity (van der Putten *et al.*, 2009). Compared to above-ground biodiversity, soil biodiversity is in general poorly understood. However, studies have already shown a wide range of controls including interactions within trophic levels (competition), interactions between trophic levels (predator-prey) and above-ground vegetation composition and density (Wardle, 2006). Initiatives to arrive at a more systematic understanding of soil biodiversity are under way (Usher *et al.*, 2006). Nevertheless, in support of the GEF Strategy on Biodiversity, targeted research on soil biodiversity, how it may be managed and what benefits may accrue is strongly indicated.

Recently the effects soil biodiversity may have on soil functioning have also received more attention, but the available information is still limited and does not (yet) allow generalized conclusions to be made. Brussaard *et al.* (2007) showed that agricultural soils with higher biodiversity are more resistant to both abiotic and biotic stresses and may process nutrients more efficiently. However, they also stated that the mechanisms which might explain these differences are not properly understood. Wagg *et al.* (2011) demonstrated that the diversity of plant-associated fungi has a direct effect on plant productivity due to their complementarity or to selection of the most efficient fungal species. More studies are available that assess the effect of (agricultural) land management on soil biodiversity. Most often, less intensive soil management has resulted in an increase in soil biodiversity (Mader *et al.*, 2002; Verbruggen *et al.*, 2010). Similar findings have been reported when conventional plowing is replaced by less intensive tillage systems or by no-till (Zida *et al.*, 2011; van Capelle *et al.*, 2012).

"Landscape of fields and homes. Indonesia." Photo: World Bank Photo Collection © Curt Carnemark

As the major primary energy source for heterotrophic soil life, soil organic carbon would be expected to be strongly related to soil biodiversity. Studies explicitly quantifying the linkages between SOC content and quality on one hand and soil biodiversity on the other have hitherto been limited and have shown associations rather than causal relationships (e.g. Wallis *et al*., 2010; Ayuke *et al*., 2011; Huerta and van der Wal, 2012). Indeed, a more diverse soil ecological community may be expected to use the available carbon resource more efficiently, thereby leading to a decrease in the SOC mean residence time and in soil carbon stocks (Wardle *et al*., 2004). Conversely, a healthy, diverse soil ecological community can only be expected when a sufficient amount of nutrients and energy (often stored in SOM) are available.

Biodiversity management within the GEF is concentrating on five objectives. It aims to (i) improve the sustainability of protected area systems, (ii) mainstream biodiversity conservation and sustainable use into production landscapes/ seascapes and sectors, (iii) build capacity to implement the Cartagena Protocol on Biosafety, (iv) build capacity for access to genetic resources and benefit-sharing, and (v) integrate obligations related to the Convention on Biological Diversity (CBD) into national planning processes.

As the achievement of objectives (iii), (iv) and (v) would not have a direct effect on SOC storage and management, these three objectives will not be discussed here. The improvement and extension of protected area systems may have significant implications for SOC storage, as there is a correlation between biodiversity and SOC storage. Just as human interventions in a landscape almost inevitably lead to a decrease in biodiversity, they generally also lead to a decrease in SOC stocks. Hence, intensively used land has lower carbon densities than natural forests or pastures (see Section 2). If land areas are protected from human impact to protect biodiversity, the SOC stocks associated with these protected areas are also protected. Protecting already degraded areas and allowing them to recover is, from the SOC perspective, even more beneficial as the decline of SOC due to human impact will at least partly be reversed, leading to carbon sequestration from the atmosphere (Guo and Gifford, 2002; Poeplau *et al*., 2011).

The most important SOC-biodiversity linkage is related to the GEF objective of mainstreaming biodiversity conservation and sustainable use into production landscapes. The key question that needs to be answered in this regard is whether and how biodiversity conservation (in a general sense) in such landscapes can be related to improved SOC storage/management. Here a distinction can be made between (i) measures that may affect biodiversity at a landscape scale, e.g. by revising the (spatial) allocation of different types of land use and protecting certain areas from human intervention; and (ii) measures taken within production areas, such as the use of alternative crops or land management techniques or the introduction of small landscape elements (e.g. hedges and ponds). Neither type of measure can be considered to be independent.

The overall effect of land management within agricultural areas can only be evaluated correctly if externalities are accounted for. For example, while organic farming is often favorable for biodiversity compared to conventional farming, when biodiversity on agricultural land is considered (Mader *et al*, 2002) yields under organic farming are on average 20-35% lower compared to conventional agriculture (Kirchmann *et al*., 2007; De Ponti *et al*., 2012; Seufert *et al*., 2012). Thus, promoting organic agriculture will provide less opportunity for land sparing (i.e. reserving large tracts of land for non-productive purposes): such spared areas may have significantly greater biodiversity than the best managed arable land.

The overall effect of organic agriculture or any other management strategy on biodiversity can therefore only be assessed if its effect on overall land use patterns is accounted for. (See also "Organic farming" under "Climate Change" below.)

While the question of the best strategy remains open from the point of view of biodiversity – see Perfecto and Vandermeer (2010) vs. Phalan *et al.* (2011) – the choices have important implications for SOC management (**Figure 4**). As a simple example, if it is assumed that, as observed by Guo and Gifford (2002), conversion of forest to arable land leads to a 40% decrease of the SOC stocks in the soil and it is also assumed that a low-input arable system reduces yields by 30%, which is similar to the average yield reduction observed under organic agriculture (Seufert *et al.*, 2012), the loss of SOC due to forest conversion to agriculture can be calculated as a function of the fraction of land that is converted to arable as follows:

For the high-intensity system, the final landscape's average carbon density will be:

$$C_D = C_{D,f}\,(1 - D_{ar}\,A_{ar})$$

$$C_D = C_{D,f}\,(1 - 0.4\,A_{ar})$$

Where:

C_D = the final carbon density

$C_{D,f}$ = the carbon density under forest

D_{ar} = the soil carbon reduction factor (here assumed to be 0.4)

A_{ar} = the amount of land converted to arable, expressed as a fraction

Thus, if all the land is converted to arable land, soil C density will be reduced to 60% of its original value, while it will be reduced to 80% of the original value if only half the land is converted.

For the low-intensity system, more arable land will be necessary. The extra amount of arable land necessary will depend on the productivity loss compared to the high-intensity system. Rearranging terms, the landscape scale carbon density can be calculated as:

$$C_D = C_{D,f}\,\left(1 - \left(\frac{D_{ar}}{P_{LI}}\right) A_{ar}\right)$$

P_{LI} = the reduction in yields under low-intensity agriculture (fraction, here assumed to be 0.7)

A_{ar} = the amount of land that would be converted to arable land under high-intensity agriculture, expressed as a fraction

Which, for the values proposed here, would finally result in:

$$C_D = C_{D,f}\,(1 - 0.57\,A_{ar})$$

Where the constant 0.57=0.4/0.7 and the fraction of arable land is the equivalent fraction that would be needed under high-intensity farming.

Thus, if 50% of the land has to be converted under high-intensity agriculture, 70% will have to be converted under low-intensity agriculture to obtain the same crop production. At the landscape scale, this would result in an additional loss of ca. 8.5% of the SOC stocks originally present. Under these assumptions, sparing would a better SOC management technique than sharing.

The outcome of the calculations presented above is critically dependent on the assumptions made with respect to yield reductions and the SOC density under high-intensity and low-intensity agricultural systems. Therefore, the result cannot be assumed to be generally valid. Our example does, however, illustrate that a landscape-scale evaluation of the effects of land use and management on SOC stocks is necessary to obtain a proper outcome.

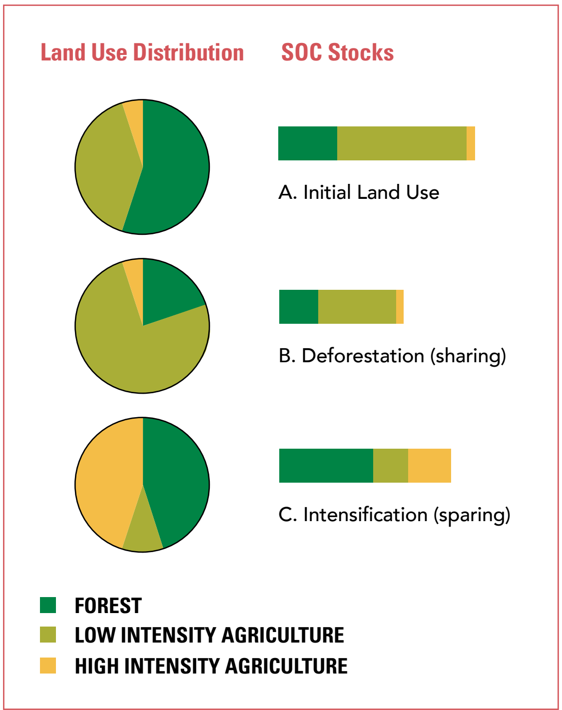


Figure 4. Land sparing vs. land sharing and SOC stocks

Note: *Increasing crop production through additional deforestation (b) may lead to additional loss of SOC in comparison to intensification of agriculture on existing arable land (c) since additional deforestation causes high SOC losses. Furthermore, SOC density on low-intensity agricultural land may be lower compared to SOC density on high-intensity agricultural land.*

CLIMATE CHANGE

The evolution of global temperatures in the 21st century remains highly uncertain for two basic reasons: (i) the development path that will be taken (and corresponding fossil fuel consumption and land use change) is unknown; and (ii) there is still considerable debate on the climate sensitivity of CO_2, i.e. the amount of warming that would result from a doubling of the atmospheric CO_2 concentration (Knutti and Hegerl, 2008). Predictions by the IPCC with respect to global temperature increases have shown a wide range (1.1-6.4°C), with the most likely values between 2 and 3°C.

Higher temperatures have been predicted toward the end of the century than those projected in the 2007 IPPC Fourth Assessment Report (AR4) (IPCC, 2007; SATC, 2012). This would be in addition to the global increase of ca. 0.8°C observed since 1900. Importantly, predictions of changes in precipitation rates and patterns are even more uncertain than those of temperature change.

While large uncertainties exist concerning the amount of carbon released by soils due to land cover change, there is no doubt that the release of CO_2 due to SOC decomposition has contributed significantly to the historical increase of atmospheric CO_2 and hence to global warming (see also Section 2). Most realistic estimates place the total net emission related to land cover change (including vegetation and soil losses) at 160-260 Pg C (Pongratz *et al.*, 2009). Lal (2004) estimated that there was a global SOC loss of ca. 76 Pg during the industrial era (1850-2000) due to land conversion, agricultural management and erosion, while the estimate by Eglin *et al.* (2010) was ca. 34 Pg for the 20th century. These estimates do not represent overall net losses from the soil to the atmosphere, as they do not account for increases in SOC storage that may be related to the increased productivity of the biosphere due to CO_2 fertilization (Eglin *et al.*, 2010). The exact results of meta-analyses of available data on CO_2 fertilization experiments depend on the statistical methods used; however, they generally confirm the positive effect of increased CO_2 levels on SOC storage predicted by models (Hungate *et al.*, 2009). The magnitude of the final effect is also dependent on other controls such as the amount of available nitrogen (de Graaff *et al.*, 2006).

Most of the GEF objectives related to climate change focus on efficient energy provision and use, as well as on enabling activities and capacity building. Objective 5, however, is to promote the conservation and enhancement of carbon stocks through sustainable management of land use, land-use change and forestry (LULUCF). To achieve this objective, the following outcomes should be achieved: (i) implementation of good management practices in forests and the wider landscape, (ii) restoration and enhancement in forests and non-forests (including peatlands), and (iii) the avoidance of greenhouse gas emissions and the sequestration

"Herdsman in the grasslands of Segou" Photo: UN Photo © Kay Muldoon

of carbon. The GEF foresees the implementation of good management practices, as well as the implementation of systems for monitoring SOC stocks, as core outputs for this objective. Below there is a focus on the possible effects of good management and a brief discussion of problems related to monitoring of SOC stocks.

The important losses of SOC due to land conversion suggest that there is at least an important theoretical potential to combat global warming by increasing the world's SOC stocks through targeted management practices. A number of researchers have drawn attention to the opportunities this could provide to developing countries (Lal, 2010). Basically, management strategies should aim to increase the C input into the soil (opening the tap, **Figure 1**) and/or to reduce the carbon decomposition rate (reducing the drain's diameter, **Figure 1**). A detailed description of potential strategies that could be applied on arable land is found in Murphy *et al*. (2011). The type of strategy that is most efficient may critically depend on other environmental variables such as soil type, landscape morphology and climate, as well as on systems aspects such as competing uses for biomass, labor constraints and access to markets. Chivenge *et al*. (2007) found that maintaining a high residue input may be most efficient on sandy soils, while reducing tillage (to minimize disturbance and the ensuing respiration) was most efficient on clayey soils. Metastudies suggest that reduced tillage or no-till may allow carbon stocks to be restored more efficiently in tropical moist climates, while the response is much smaller in dry, temperate climates (Ogle *et al*., 2005).

Reduced tillage or no-till

Potential gains in SOC are largest when soils are not yet saturated with carbon, as these soils have the greatest potential to physically protect additionally supplied organic matter from decomposition (Angers *et al*., 2011). SOC stocks in most agricultural soils are currently well below saturation. Management techniques that reduce soil disturbance, such as reduced tillage or no-till, may therefore allow to sequester significant amounts of C an arable land (Lal and Kimble, 1997). Recent studies, however, suggest that earlier estimates of carbon sequestration under no-till were probably too optimistic, partly due to measurements being restricted to the soil's top layer so that redistribution of SOC within the profile was not properly accounted for (Manley *et al*., 2005; Angers and Eriksen-Hamel, 2008). Angers and Eriksen-Hamel (2008) reported an overall average increase in SOC of less than 5 Mg C ha^{-1} under no-till as compared to conventional plowing for studies lasting between 5 and ca. 40 years: this increase was only weakly related to the duration of the study. Corresponding sequestration rates vary between 0.12 and 1 Mg C ha^{-1} yr^{-1}.


"Farming in the Gorkha Region, Nepal" – Photo: GRID-Arendal © Wenzel Prokosch

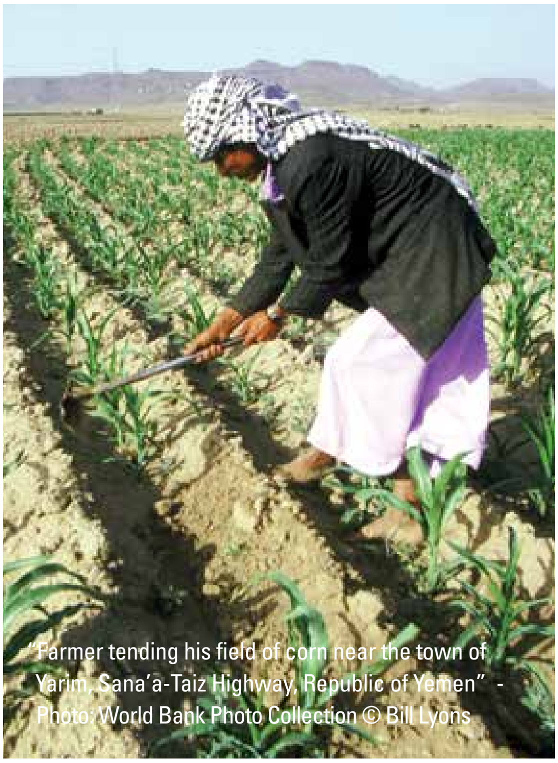
Ogle *et al*. (2005) did not report absolute values, but estimated the overall increase in SOC stocks under no-till in the 0-0.3 meter soil layer after 20 years to be ca. 20% in the tropics and ca. 13% in temperate areas compared to continued conventional plowing. Assuming realistically that plow layers under arable land contain between 0.7 and 2% SOC and have a bulk density of ca. 1350 kg m^{-3}, carbon densities for these plow layers vary between 28 and 81 Mg C ha^{-1}. This implies that conversion from conventional tillage to no-till would result in sequestration rates of 0.30-0.80 Mg C ha^{-1} yr^{-1} in the tropics and 0.18-0.52 Mg C ha^{-1} yr^{-1} in temperate areas. Eagle *et al*. (2012) reviewed all available information for the United States and arrived at an overall average sequestration rate of 0.33 Mg C ha^{-1} yr^{-1} under no-tillage. Sanderman *et al*. (2010) reviewed available data for Australia and reported an average gain of ca. 0.34 Mg C ha^{-1} yr^{-1}. However, their data also showed that the magnitude of the gains was clearly related to sampling depth: gains were on average 0.64 Mg C ha^{-1} yr^{-1} when only the 0-0.045 meter soil layer was considered, but were 0.11 Mg C ha^{-1} yr^{-1} when soils were sampled to a depth of 0.44 meter.

Follett (2001) proposed values of 0.3-0.6 Mg C ha^{-1} yr^{-1} for conservation tillage (i.e. reduced tillage while maintaining a significant residue cover on the surface). Although this estimate is in the same range as those proposed for no-till, actual gains from reduced tillage may be expected to be smaller in comparison to those from no-till since reduced tillage causes some soil disruption and brings residues in close contact with the soil matrix (Murphy *et al*., 2011). This is confirmed by the review of Eagle *et al*. (2012), who obtained an average sequestration rate of 0.12 Mg C ha^{-1} yr^{-1} for conservation tillage in the United States.

The need for caution is confirmed in a study by Christopher *et al*. (2009) that covered three Midwestern states in the United States. They found that no-till led to a significant increase in SOC storage in only 1 out of 12 study areas: in 3 study areas there was a net loss of SOC under no-till. Recent sequestration rates reported for Canada were also much lower than those proposed in earlier studies, ranging between 0-0.14 Mg C ha^{-1} yr^{-1} (VandenBygaart *et al*., 2010). Similarly, in France Oorts *et al*. (2007) found differences in SOC stocks down to 0.3 meter between no-till and conventional tillage after 32 years to be no greater than 10-15% to the advantage of no-till. This is equivalent to a sequestration rate of ca. 0.175 Mg C ha^{-1} yr^{-1} under no-till. However, the largest part of this difference (66%) was accounted for by unprotected carbon (particulate organic matter and fresh residues), implying poor stabilization and very likely loss following a single disturbance. Furthermore, care should be taken not to extrapolate experimentally observed sequestration rates to longer time spans: replenishing the soil carbon store will inevitably lead to the establishment of a new equilibrium, limiting potential storage gains to a maximum of several decades (Lal, 2004).

Peatlands

Peatlands contain a disproportionally large amount of SOC. According to the most recent estimates, they store ca. 277 Pg (Tarnocai *et al*., 2009). Wet, undisturbed peatlands naturally sequester carbon because mineralization rates are very low, leading to the continuous accumulation of plant residues. Natural C accumulation rates in circumpolar areas are estimated to be ca. 0.3 Mg C ha^{-1} yr^{-1} (Backstrand *et al*., 2010; Koehler *et*



"Farmer tending his field of corn near the town of Yarim, Sana'a-Taiz Highway, Republic of Yemen" - Photo: World Bank Photo Collection © Bill Lyons

"Aerial View of Forest, Indonesia" Photo: World Bank Photo Collection © Curt Carnemark

al., 2011), but methane emissions from these wet environments significantly reduce their net climatic effect (Backstrand *et al.*, 2010). Several studies have shown that SOC losses over the last decades mainly occurred from waterlogged soils and/or peatlands that had been subjected to drainage, thereby increasing SOC decomposition rates (Bellamy *et al.*, 2005; van Wesemael *et al.*, 2010). Restoring natural drainage conditions may therefore greatly benefit SOC preservation and may help sequestration. However, quantifying such effects is currently impossible due to a lack of experimental data, especially for non-circumpolar peat areas.

Forests

Forests contain the largest part of the global SOC stocks. SOC density in natural, undisturbed forests is likely to increase in the near future due to CO_2 fertilization. Considering the great difference in carbon density between forests and agricultural land, conversion of cropland to forests will lead to significant increases in SOC storage (Guo and Gifford, 2002; Laganiere *et al.*, 2010; Poeplau *et al.*, 2011; Chang *et al.*, 2012). However, the way existing forests are managed may also have significant impacts on SOC stocks. In a model simulation study, Hashimoto *et al.* (2012) found that different management techniques in Japanese forests could result in differences in SOC density of up to 10 Mg C ha^{-1}. Longer rotations and leaving the residues of thinned trees in the forest increased the predicted SOC density. Imai *et al.* (2009) reported an increase in landscape-scale C storage of 60 Mg C ha^{-1} in Indonesia following the introduction of sustainable forest management techniques, but pointed out that differences in SOC storage were minimal. This may be related to the longer response time of SOC compared to above-ground biomass. Data on the effects of forest management techniques on SOC storage are, however, still very limited.

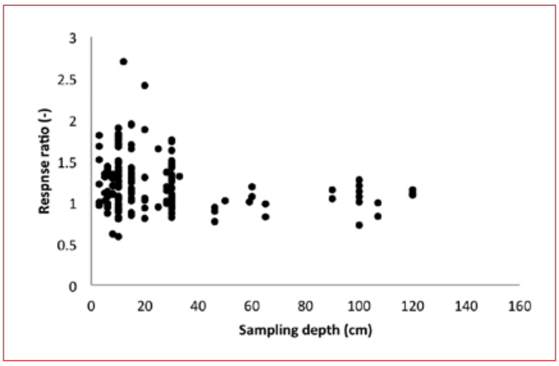


Figure 5. Response ratio (ratio of depth of integrated SOC stocks in alternatively managed or converted grassland to depth of integrated SOC stocks in traditionally managed grassland) vs. sampling depth (cm)

Note 1: *As calculated from data compiled by Conant et al. (2001).*

Note 2: *The response ratio generally decreases with increasing sampling depth, an observation also made by Manley et al. (2005).*

Grasslands

Grasslands may be the only biomes where sound management might allow SOC stocks to be increased above their natural equilibrium values. The data summarized by Conant *et al.* (2001) suggest that for most management techniques, such as fertilization and improvement of grazing management, average increases in the SOC content of the 0-0.3 meter horizon are of the order of 1-2% per year, corresponding to average sequestration rates of 0.3 Mg C ha^{-1} yr^{-1}, but the variations are large. Much higher rates were reported for a small number of studies focusing on the effects of the introduction of earthworms or alternative grass species. Potential sequestration may depend on climate and other environmental variables, but data to securely quantify those trends are not yet available (Conant and Paustian, 2002).

Again, care must be taken not to overestimate the sequestration potential. The relative increase in SOC observed is strongly dependent on the depth sampled, with very few studies showing a significant effect when sampling includes the subsoil (**Figure 5)**. The failure to detect statistically significant differences between different treatments when deeper soil horizons are included is, however, not a proof that significant differences do not exist. Changes in management techniques may cause a redistribution of C within the profile. It is therefore important that sampling is carried out to a sufficient depth, so that redistribution can be accounted for (Angers and Eriksen-Hamel, 2008). Yet the C content of deeper horizons is known to be highly variable. This may lead to a situation where differences in whole-profile SOC stocks cannot be statistically detected without taking an excessive number of samples, even if there is a significant increase in topsoil SOC content (Franzluebbers, 2010; Kravchenko and Robertson, 2010). Kravchenko and Robertson (2010) concluded from their study that SOC stocks should be assessed on a horizon by horizon basis, and that conclusions concerning the whole profile should be based on the comparison of SOC stocks of individual soil horizons. The number of replicates needed for each soil horizon in order to reliably detect significant C change needs to be carefully determined.

Agroforestry

There is considerable literature advocating the strong potential benefits of combinations of trees and annual or perennial crops in mixed systems, including with respect to carbon sequestration (e.g. Dixon *et al*., 1993; Ramachandran Nair *et al*., 2009). Recent recommendations on potential soil carbon sequestration rates that may be obtained by different agroforestry systems suggest high to very high SOC sequestration potentials (Ramachandran Nair *et al*., 2009). Depending on climate and soil type, proposed SOC sequestration rates vary between 0.25 Mg C ha^{-1} yr^{-1} for arid and semi-arid lands and > 5 Mg C ha^{-1} yr^{-1} for silvopasture systems in tropical humid lowlands and tropical highlands.

However, the experimental evidence on which such estimates are based is poor. Ramachandran Nair *et al*. (2009) refer to Nair *et al*. (2009) as a main data source. We have re-analysed all the literature cited in the latter publication and complemented it with some more information found in recent literature and in Oelbermann *et al*. (2004). It appears that there is very little evidence substantiating that SOC sequestration rates higher than 1 Mg C ha^{-1} yr^{-1} can be achieved for extended periods. In well-managed systems rates of 0-0.5 Mg C ha^{-1} yr^{-1} appear to be likely, although the reported data may miss some SOC stored at depth due to the die-off of tree roots. Part of the confusion may be due to the fact that agroforestry systems indeed often lead to significantly increased above-ground C inputs into the soil (0.3-4.6 Mg C ha^{-1} yr^{-1}, Oelbermann *et al*., 2004), but inputs (opening the tap, **Figure 1**) do not directly translate into storage rates as, almost inevitably, mineralization rates (discharge through the drain, **Figure 1**) will also increase, albeit not necessarily at the same rate.

"Mountainous Agriculture"
Photo: Global Environment Facility (GEF)

Table 3. SOC sequestration rates measured under agroforestry systems

REFERENCE	LOCATION	SYSTEM	SOC SEQUESTRATION RATE (Mg C ha^{-1} yr^{-1})	SAMPLING DEPTH	COMMENT
(Lenka *et al.*, 2012)	Eastern India	Various techniques to reclaim degraded land	0	0-0.3m	Reclamation led to significant SOC storage (2-3 Mg C ha^{-1} yr^{-1}), but presence of trees did not help
(Veum *et al.*, 2011)	Missouri, claypan region	No-till vs. grass filter strips vs. agroforestry filter strips, 10 yrs	0	NA	No significant differences in total SOC between systems
(Salazar *et al.*, 2011)	Chile, Mediterranean zone	Agroforestry in combination with water harvesting vs. other systems, 12 yrs	0	NA	No significant differences in total SOC between systems
(Peichl *et al.*, 2006)	Southern Ontario, Canada	Tree-based intercropping (poplars), 13 yrs	ca. 1	NA	Significant SOC increase under poplars
(Peichl *et al.*, 2006)	Southern Ontario, Canada	Tree-based intercropping (spruce), 13 yrs	0	NA	Spruce did not lead to any SOC enhancement
(Sharrow and Ismail, 2004)	Western Oregon, USA	Agroforests vs. pastures, 10 yrs	0		No significant difference in SOC content
(Oelbermann *et al.*, 2004)	Canada	Alley cropping, 10 yrs	0	0–0.2	No significant differences in SOC stocks
(Oelbermann, 2002)	Costa Rica	Alley cropping, 10 yrs	0	0–0.2	No significant differences in SOC stocks
(Oelbermann, 2002)	Costa Rica	Alley cropping, 19 yrs	0.25	0–0.2	Same tree as study above (*E. poeppigiana*) but longer monitoring time
(Oelbermann, 2002)	Costa Rica	Alley cropping, 10 yrs	1.1	0–0.2	*G. Sepium trees*
(Oelbermann, 2002)	Costa Rica	Alley cropping, 19 yrs	0.42	0–0.2	*G. Sepium trees*
(Schroth *et al.*, 2002)	Amazonia	Multistrata system, 7 yrs	0.45	0–0.15	
(Chander *et al.*, 1998)	India	Alley cropping, 13 yrs	0	0-0.15	*Dalbergia sissco*
(Mazzarino *et al.*, 1993)	Costa Rica	Alley cropping, 10 yrs	0.47	0–0.1	*E. poeppignia*
(Mazzarino *et al.*, 1993)	Costa Rica	Alley cropping, 10 yrs	0.44	0-0.1	*G. Sepium*
(Haggar, 1990)	Costa Rica	Alley cropping, 6 yrs	0.81	0–0.2	*E. poeppigiana*
(Haggar, 1990)	Costa Rica	Alley cropping, 6 yrs	0.2	0–0.2	*G. Sepium*
(Diels *et al.*, 2004)	Ibadan, Nigeria	Alley cropping, 16 yrs	0.12	0.4	No net gain in SOC: decrease in SOC was less rapid under alley cropping (*L. leucocephala* and *Senna siamea*) in comparison to treeless systems

"A farmer gathers wheat in Bamyan, Afghanistan" Photo: UN Multimedia © Eric Kanalstein

Organic Farming

Similar concerns may be raised with respect to the benefits of organic farming for SOC sequestration. Again, the kitchen sink example (**Figure 1**) may clarify this. Organic agriculture generally leads to lower yields, although the effects vary from crop to crop (Seufert *et al.*, 2012). Hence, the input (the tap discharge) of organic matter into the soil may decline. A gain in SOC stocks can then only be obtained if, at the same time, respiration rates go down (the diameter of the drain decreases), e.g. due to a change in the composition and/ or activity of the microbial community in the soil. Data available on specific respiration rates under organic agriculture (i.e. the respiration rate per unit of C) challenge this assumption (Leifeld, 2012). In most systems analyzed by Leifeld (2012) specific respiration appeared to increase, which could lead to SOC losses rather than gains in the long term. Such losses may be compensated for by the input of external C (e.g. the application of farmyard manure), leading to higher SOC stocks under organic agriculture as compared to conventional systems, in particular conventional systems where only mineral fertilization is used (Birkhofer *et al.*, 2008). However, that necessarily means the organic C is imported from elsewhere and therefore this is most likely not a net gain at the system scale (Powlson *et al.*, 2011). A full SOC budget for organic farming would also necessarily include additional losses due to the need for more land (see above).

Alternative Management Systems

Finally, it should be made clear that, especially on agricultural land, increasing SOC stocks through alternative management is not always equivalent to climate change mitigation. If organic carbon sources such as manure and/or residues are used, there is most often no net gain as the organic carbon is likely to have been used elsewhere if it was not applied to the parcel under consideration. Changes in management practices that lead to an increase in soil moisture (e.g. use of no-till in humid areas) may also lead to extra emissions of N_2O, which could completely offset gains from increased SOC storage (Powlson *et al.*, 2011). Similarly, when crop productivity is increased through the use of artificial fertilizers the CO_2 cost of fertilizer production – estimated at 3.11 kg of CO_2 for 1 kg of nitrogen (N) by West and Marland (2002 a,b) and 5 kg of CO_2 for 1 kg of N by Powlson *et al.* (2011) – needs to be accounted for and balanced against the increase in the soil SOC stocks on the arable land where the fertilizer is applied, as well as the loss of SOC stocks that may be avoided because less land needs to be taken into production.

Soil Erosion — Photo: iStockphoto ©Berryspun

LAND DEGRADATION

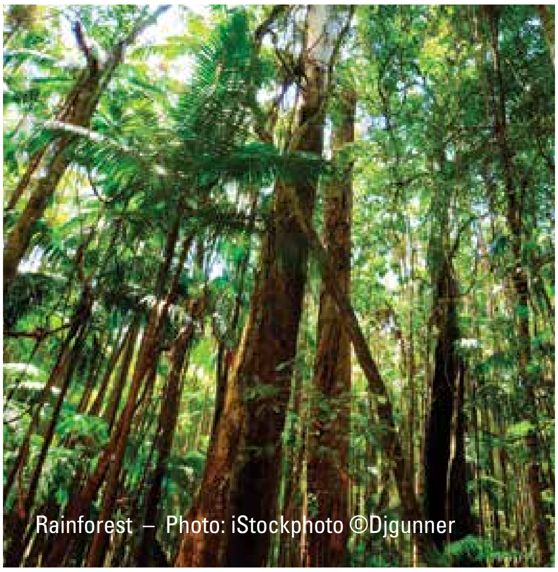
Within the GEF, land degradation is approached broadly. Proposed mitigation strategies focus on *maintaining and/or improving the flow of agro-ecosystem services to sustain livelihoods of local communities* (***Objective 1***) and on *generating sustainable flows of forest ecosystem services in arid, semi-arid and sub-humid zones* (***Objective 2***) while, at the same time, attempting to reduce human pressures on natural resources (***Objective 3***). To facilitate the GEF Strategy for the Land Degradation Focal Area, the GEF aims to *increase the capacity to apply adaptive management tools in sustainable land management* (***Objective 4***) (GEF, 2011). This broad approach implies that any loss of the land's capacity to support local livelihoods with the ecosystem services they need (e.g. by providing water, food and fiber) is seen as land degradation.

Soil Erosion

An important land degradation process often associated with large losses of SOC is soil erosion. Agricultural soil erosion is a serious problem, although its magnitude may have been overestimated in the past. Annual rates of agricultural soil erosion by water are currently estimated to mobilize ca. 30 Pg of agricultural soil and the associated SOC (Quinton *et al.*, 2010). However, this mobilization of soil does not immediately lead to release of SOC to the atmosphere. Most of the soil and associated carbon is redeposited on land or in aquatic sediments, where it is stored for considerable periods (Stallard, 1998; Van Oost *et al.*, 2007). Furthermore, some of the SOC removed from eroding sites is replaced through "dynamic replacement" (Harden *et al.*, 1999; Berhe *et al.*, 2008). SOC mineralization rates in eroded soils during or just after erosion events appear to be limited (Wang *et al.*, 2010; Van Hemelryck *et al*, 2011). Overall, soil erosion is currently estimated to cause a relatively minor decrease in SOC (Van Oost *et al.*, 2007; Harden *et al.*, 2008). Reducing erosion will therefore not greatly contribute to an increase of SOC stocks.

This does not mean, however, that reclamation of degraded lands would not be beneficial for SOC storage. If degradation processes are allowed to continue to the point where the soil's productivity is significantly reduced, dynamic replacement will become less important and, for such ecosystems, soil erosion may become a net source of emissions to the atmosphere (Quinton *et al.*, 2010). Restoring productive agricultural systems on such lands is perhaps the best strategy for rapid SOC sequestration. These soils are usually strongly depleted in SOC (i.e. the kitchen sink is nearly empty), so that C inputs are more likely to be translated into additional storage (Lenka *et al.*, 2012). These may be the sole conditions under which SOC sequestration rates exceeding 1 Mg C ha^{-1} yr^{-1} may be achieved for extended periods. However, such rates will only be achieved in well-managed systems and when sufficient nutrients are supplied.

As outlined above, SOC stocks will be affected by any management strategy designed to optimize land allocation and/or land management. At the same time, a sustainable management strategy needs to take SOC management into account as healthy SOC stocks may make it possible to achieve sustainability aims. It is critical to understand that these aims are not contradictory. Above, a simple example of high-productivity agriculture that allows the safeguarding of a significant fraction of the SOC present in the landscape under natural conditions was elaborated. Let us now assume that an increase of agricultural production in the area is necessary to supply sufficient food to a growing population. Additional deforestation will lead to additional SOC losses. Not only will increasing the productivity of

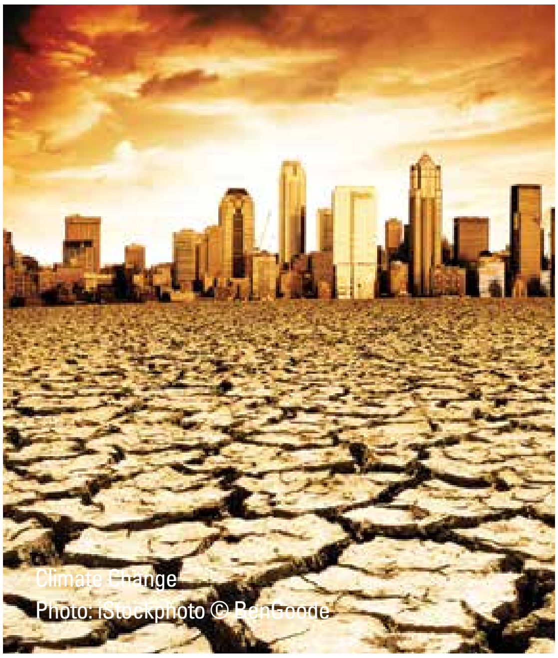


Rainforest – Photo: iStockphoto ©Djgunner the arable land already under production (e.g. by eliminating ley periods) allow safeguarding the SOC in the forested land, but increasing the productivity of existing arable land will also increase the carbon input into the arable land (through increased root and residue production), thereby creating additional potential to store SOC (VandenBygaart *et al.*, 2010; Minasny *et al.*, 2012). At the same time, more forest will remain available to deliver forest ecosystem services and maintain biodiversity (**Figure 4**).

Thus, while agricultural intensification is often (and rightly) associated with important negative externalities, it should not be considered as negative *per se*. Burney *et al.* (2010) estimate that, since 1961, the emission of ca. 161 Pg C has been avoided globally due to intensification, mainly through the avoidance of additional conversion of natural land to cropland.

INTERNATIONAL WATERS

Improved protection and management of international waters will not directly affect SOC storage. However, ocean acidification is now recognized as one of the main problems for many marine ecosystems (Doney *et al.*, 2009).
An important fraction (currently the equivalent of ca. 2.2 Pg of C yr^{-1}) of the CO_2 emitted by humans is absorbed by the oceans (Le Quere *et al.*, 2009). While that helps to mitigate global warming, it leads to the production of carbonic acid in the oceans. This has already resulted in a measurable increase in acidity, which has detrimental effects on marine wildlife, especially on calcifying organisms (i.e. organisms that build shells out of calcium carbonate extracted from ocean water) (Pandolfi *et al.*, 2011). Storing more carbon will reduce acidification rates and therefore help to preserve marine wildlife.


Climate Change
Photo: iStockphoto © BenGoode

PERSISTENT ORGANIC POLLUTANTS

Soils are important reservoirs of persistent organic pollutants (POPs). Their capacity to store POPs is strongly dependent on their SOC content, although the affinity between a chemical and SOC varies with the chemical's properties (Sweetman *et al.*, 2005). However, concentrations of POPs are not uniquely determined by SOC content or other soil properties. Variations in current and past application rates of herbicides and pesticides, distance from industrial sources, air transport and precipitation, runoff, re-volatilization, and microbial decomposition, are some of the major factors governing the levels and dynamics of POPs and other pollutants in soils (Jones and de Voogt, 1999; Newman, 2009; Villanneau *et al.*, 2011).

The strong affinity between SOC and POPs implies that if land conversion or a change in land management techniques result in a decrease in SOC stocks, stored POPs may be released into other environmental compartments (e.g. groundwater) where they may be even less desirable. On the other hand, greater SOC contents also lead to dissolved organic carbon (DOC leaching into the subsoil, creating opportunities for facilitated transport (Totsche *et al.*, 2006)). Not only total SOC contents and mobility, but also the type of SOC strongly influences retention of POPs. Greater black carbon content increases sorption of herbicides (Yang and Sheng, 2003) and of polycyclic aromatic hydrocarbons (PAH) (Cornelissen *et al.*, 2005). The relationship between the soil's SOC content and its capacity to degrade pollutants is unclear: while a high SOC content may reduce the availability of the pollutant to the microbial community for degradation, it may increase microbial activity in general (Sweetman *et al*, 2005).

HOW SOIL ORGANIC CARBON MANAGEMENT CAN DELIVER MULTIPLE BENEFITS

How SOC management may contribute to and be affected by the GEF objectives was described in some detail in Section 4. Potential benefits in relation to these aspects are therefore not discussed further in this section. Instead, other important aspects of agro-ecological systems that would be affected by SOC management are examined. What the economic costs and benefits associated with proper SOC management could be is outlined, and a vision is presented of how to move forward toward optimal SOC management.

SOC MANAGEMENT AND SOIL QUALITY

There is a large body of literature describing the beneficial effects of SOC on aspects of soil quality other than biodiversity (which has already been discussed in Section 3; see Loveland and Webb (2003) and Stringer *et al*. (2012) for more references). Perhaps the first beneficial effect of SOC to be documented is its effect on soil aggregate stability and structure. It has long been established that soils with a higher SOC content generally have a higher aggregate stability (Stengel *et al.*, 1984). This effect works both ways, as aggregation physically protects SOC (Six *et al.*, 2000). Higher aggregate stability reduces slaking and crusting, with direct implications for water infiltration and erosion (see below). An increase in SOC is often thought to improve the soil's water holding capacity, but experimental support for this assertion is remarkably poor and ambiguous (Loveland and Webb, 2003). The presence of SOC also reduces the vulnerability of a soil to erosion. This effect was already incorporated in the formulation of the soil erodibility factor in the Universal Soil Loss Equation (Wischmeier and Smith, 1965). The analysis of Torri and Poesen (1997) showed that the impact of SOC on erodibility is dependent on soil texture, as erodibility is related to the ratio of SOC content to clay content.

The effect of SOC on erosion resistance is mainly explained by its positive effect on soil structure and aggregate stability. High levels of SOC make aggregates more resistant to slaking, allowing more water to infiltrate (LeBissonnais and Arrouays, 1997). The precise magnitude of the effect (i.e. the degree to which erosion is reduced by SOC management) is more difficult to assess, as it may again depend on other factors including the spatial scale at which erosion is assessed. However, management systems aimed at reducing erosion often include the use of cover crops or the maintenance of a residue cover, which may also enhance SOC stocks: these techniques are highly efficient in reducing erosion (Leys *et al.*, 2010). This is a very important additional benefit, not only because crop yields are negatively affected by soil erosion (Bakker *et al.*, 2004) but also because erosion induces a loss of nutrients from the agricultural system that may even be larger than the annual application rate (Quinton *et al.*, 2010).

SOC MANAGEMENT AND AGRICULTURAL YIELDS

Given the clear effect of SOC stocks on overall soil quality, it is not surprising that the link between SOC levels and crop yield captured scientific attention several decades ago (e.g. Allison, 1973). Many studies have reported such a positive relationship: a recent overview can be found in Lal (2010).

It should be kept in mind that a *positive* relationship between crop yields and SOC content does not on its own imply a casual relationship. First, organic amendments will not only bring C to the soil, but also nutrients. Hence, increased crop productivity may be due to the availability of additional nutrients rather than an increase in soil quality due to the presence of SOC. Edmeades (2003) reviewed the literature on the effects of manure amendments on soil quality and crop yields. While manure significantly increased soil quality (e.g. through increases in soil organic carbon stocks, aggregate stability, soil hydraulic conductivity, porosity and microfauna), no direct link could be established statistically between manure application and crop yield when fields with manure application were compared with fields to which the same amounts of nutrients had been applied using chemical fertilizer. Thus, organic amendments did boost crop yields, but the same boost was achieved with a balanced application of chemical fertilizers. This indicates that most soils have adequate SOC contents for a particular crop and that greater SOC *per se* does not improve productivity. More recent studies have reached similar conclusions, sometimes even indicating a slight loss of yields when manure was used in comparison to chemical fertilizers, which may be attributed to the nutrients in manure not being optimally balanced for plant growth or not being immediately available to the crop (Ludwig *et al.*, 2011; Yan *et al.*, 2012).

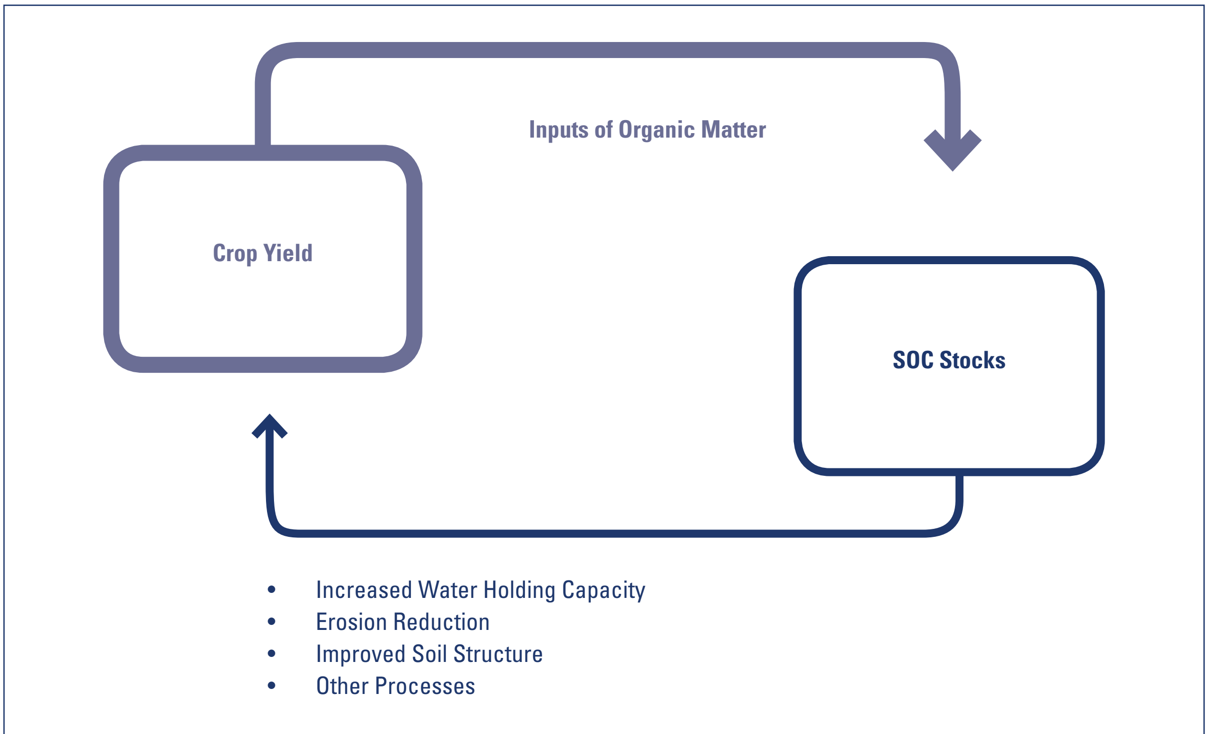


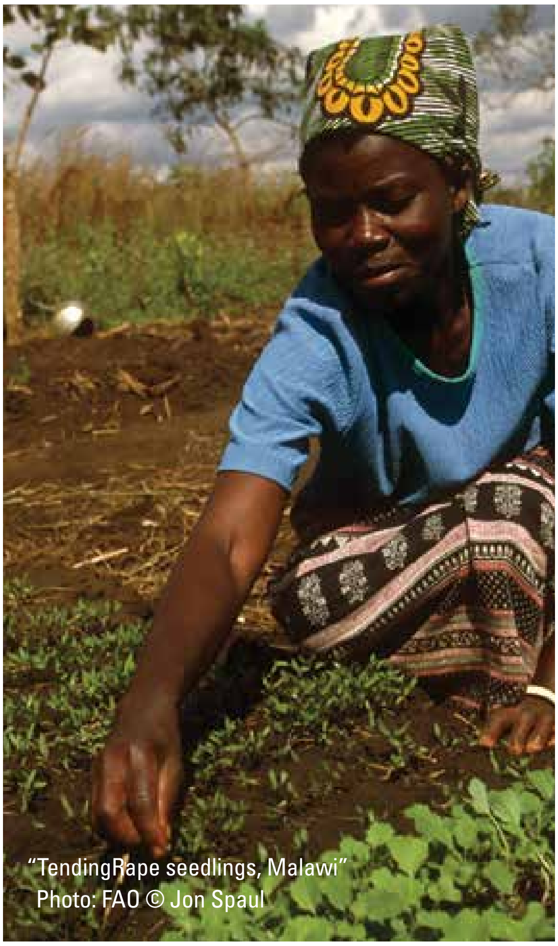
Figure 6. Coupling between SOC stocks and crop yield

Note: *While increasing SOC stocks may increase crop yields through various mechanisms, the reverse is also true: increasing crop yields leads to higher SOC stocks. Literature data show that this coupling from crop yield to SOC stocks is quantitatively more important than the reverse (see text). Hence, the positive relationship often found between SOC stocks and crop yields should be interpreted correctly.*

Second, when yields are increased (e.g. through the application of fertilizers, the selection of more appropriate cultivars and/or better water management) the production of plant residues and roots will generally also increase, albeit not at the same rate the harvest index generally increases over time (Tian *et al*., 2011). This results in a higher C input into the soil (opening the tap, **Figure 1**). Hence, SOC stocks may be expected to increase in well-managed agricultural systems in which yields increase, as was experimentally found by Rasool *et al*. (2007), Zingore *et al*. (2007) and Kukal *et al*. (2009). Increasing yields is probably also the main explanation for the increase in SOC stocks at a regional level reported by Benbi and Brar (2009), Minasny *et al*. (2011) and Minasny *et al*. (2012), and for the better preservation of SOC stocks in long-term trials when artificial fertilizer is used reported by (Ladha *et al*., 2011). Conversely, if the implementation of alternative management techniques would result in yield depression, this may negatively affect SOC stocks (Ogle *et al*., 2012). Thus, positive relationships between SOC stocks and crop yields such as those found by (Pan *et al*., 2009) should not be interpreted only as an improvement of yields by greater SOC: better yields may be expected to result in higher C inputs into the soil (opening the tap), suggesting a chicken-and-egg conundrum (**Figure 6**). It is therefore no surprise that some researchers see an increase of chemical fertilizer use and of fertilizer efficiency as perhaps the most important strategy for increasing SOC stocks on agricultural land in West Africa (Bationo *et al*., 2007).

Given that the causal relationship between SOC stocks and crop yields is not always apparent, is it worthwhile to attempt to increase SOC stocks from a farming perspective? The answer is yes. Although increasing SOC alone may not be enough to improve crop yields, the maximum yield potential is often only achieved in soils with greater SOC contents (Ngoze *et al*., 2008). Because of the multitude of possible soil chemical, biological and physical constraints to realizing the yield potential, improving SOC contents is an important insurance against crop failure from a soil perspective and may be the best strategy to restore fertility on degraded land, for example when the soil's water holding capacity is the major yield constraint (Bruce *et al*., 1995).

An important issue is that increasing SOC stocks may not directly lead to higher yields, but may help to reduce yield variability. Given that SOC increases physical soil fertility (through increasing the water holding and regulation capacity) as well as the potential to store and buffer nutrients, soils with higher SOC stocks may be capable of better buffering temporary shortages in water and/or nutrients, leading to a decrease in crop yield variability. This may result in important gains in rural livelihood quality, food security and income. Some studies, such as that of Pan *et al*. (2009), report a decrease in yield variability with increasing topsoil SOC content, but this is not generally confirmed (e.g. Yan and Gong, 2010). Furthermore, given the two-way interaction between SOC stocks and crop productivity, a gain in SOC (in a degraded agricultural system) may be seen as an important indication that the system is improving and becoming more sustainable.


"TendingRape seedlings, Malawi"
Photo: FAO © Jon Spaul

"A farmer harvests corn (maize) in Copan Ruinas, Honduras" – Photo: World Bank Photo collection © Alfredo Spur

SOC MONITORING

SOC monitoring is an essential component of any SOC management project. Changes in SOC stocks need to be monitored to assess the effectiveness of the project and to take these changes into account in national carbon budgets. Yet in monitoring changes in SOC stocks due to management there are two important difficulties.

First, SOC stocks show high spatial variability. This is true even within landscape units that appear at first sight to be spatially homogeneous, particularly in the case of carbon stored in deeper soil horizons (Don *et al.*, 2007; Rumpel and Koegel-Knabner, 2011). A large number of samples may therefore be necessary to detect differences in SOC stocks. (Smith, 2004) estimated that, for a land unit with minor variations in SOC stocks (< 25%), over 100 samples would be needed to detect a 3% increase (with reference to the original value) in the SOC stocks. Saby *et al*. (2008) calculated the mean detectable change in SOC for various countries in Europe based on existing monitoring schemes. For most countries, changes in average SOC content between 0.3 and 3% (with reference to the total soil mass) would be necessary in order to be statistically detectable using current monitoring schemes. This implies that changes resulting from arable land management cannot be reliably detected on an annual basis: a change in the existing SOC stocks at a rate of 0.6% per year relative to the original SOC stocks can only be detected after ten years or more in most countries.

Second, changes in SOC due to management will be superimposed on changes that occur because of climate change and CO_2 fertilization, which can be expected to be of similar magnitude to management effects. Therefore, it may be difficult to disentangle these effects (**Figure 7**). Assessing the effect of soil management on SOC sequestration requires a proper baseline to be established. The reference would consequently not be a constant value, but would indicate how SOC stocks are expected to change in the absence of any change in management technique (due to climate change and CO_2 fertilization, **Figure 7**).

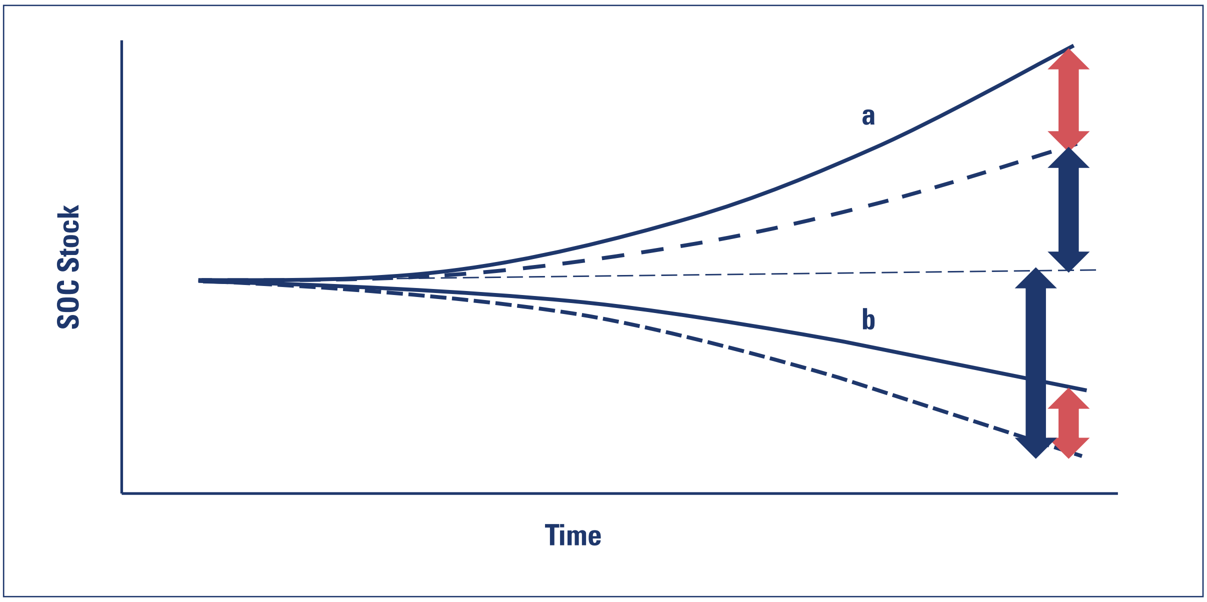


Figure 7. Evolution of SOC stocks due to management and other factors

Note: *The dotted lines and blue arrows indicate the evolution of SOC stocks in the absence of any management change: this would be positive under (a) and negative under (b). In both cases improved management leads to a relative increase in SOC stocks, as indicated by the red arrows. However, a decline in SOC stocks is observed under (b) simply because effects other than management (changes in climate) are more important than management effects.*

"Fresh vegetables" – Photo: iStockphoto © Ann Steer

The main objective of soil monitoring networks (SMN) in agricultural systems is to scale up the SOC stocks measured within a field to a region with similar soil and management, or to the agricultural soils of an entire country. As an alternative to the lumped approach to detecting changes in SOC stocks based on the minimum detectable difference, SOC conditions at SMN sites can also be attributed to similar soil/land use/climate units. Simulation models can be used to predict the SOC change in such units (Milne *et al*., 2007). Ogle *et al* (2007) used a similar approach to compare SOC stocks predicted by the Century model with observed SOC stocks in 872 treatments of 47 long-term experiments.

Some recommendations on the design, sampling and analytical procedures of SMNs can be given (van Wesemael *et al*., 2011): (i) The exact position of composite samples (4–10 sub-samples) should be recorded and marked in the field (e.g. with buried antennas); (ii) Soil samples should be archived to avoid biases induced by changes in analytical procedures or analysts over time; (iii) Records of crop/grass production and agricultural practices are required when sites are used as input for process-based models; (iv) Samples should be taken at multiple fixed depth intervals; (v) Bulk density, rock fragment content and large pieces of organic debris should also be determined in order to convert SOC concentrations of the fine earth into SOC stocks and correct for soil compaction. In fact, SOC stocks should, whenever possible, be expressed on an equivalent mass basis rather than over a fixed depth (Ellert and Bettany, 1995).

Spectroscopy techniques using the visible and near-infrared (VNIR) or mid-infrared (MIR) wavelength have been developed as a cheap and high-throughput alternative to conventional CN analyzers (Vasques *et al*., 2010a; Leone *et al*., 2012; McDowell *et al*., 2012). Calibration models developed from a Europe-wide SMN revealed that although the accuracy of C estimates derived from spectral measurements still lagged behind the estimates of CN analyzers, the bias of spectral measurements is very low, yielding reliable country or regional average SOC contents (Stevens *et al*., 2013). Janik *et al*. (2007) developed a calibration model from which not only total organic carbon, but also particulate and charcoal carbon can be predicted using MIR spectroscopy, and demonstrated that the calibration model developed for Australian soils was also effective for Kenyan soils. Similarly, Vasques *et al*. (2009) demonstrated that various soil carbon fractions representing different carbon pools can be estimated using VNIR diffuse reflectance spectroscopy and can confidently be upscaled to the landscape level. Spectrometers have also been mounted on airborne platforms (Stevens *et al*., 2012) and have produced detailed maps of the SOC content in the plow layer of bare soils. Although this technique is not yet operational for routine applications, corrections for interferences such as water vapor in the atmosphere, soil moisture, residues and roughness are being developed and hyperspectral satellites (e.g. EnMap) will be launched in the near future. The fact that measurements are only possible when the vegetation cover is relatively sparse creates limitations for remote sensing methods. Nevertheless, these developments offer potential for the rapid collection and updating of data on SOC stocks, including in environments which are not easily accessible. They will contribute to more dynamic and spatially better resolved monitoring of SOC in soils, within the more general framework of digital soil mapping (Grunwald *et al*., 2011). Further development of the latter is indispensable to achieve better and more sustainable use of the global soil resource.

COSTS AND BENEFITS

The most direct (and perhaps the most important) cost related to SOC losses and gains follows from the fact that SOM does not consist of C only, but also contains substantial amounts of organic nitrogen (N_{org}) and organic phosphorus (P_{org}): these nutrients therefore need to be available to enable SOC sequestration (Lal, 2004; Kirkby *et al.*, 2011). The average C:N_{org} ratio on arable land varies over a relative small range (8-12), while the C:P_{org} ratio is much more variable and averages around 50 (Quinton *et al.*, 2010; Kirkby *et al.*, 2011). Storing 1 Pg of C implies storing 80-125 Tg of N (an amount approximately equal to the annual global chemical production of nitrogen fertilizer) and ca. 20 Pg of organic P. Providing these nutrients at 2012 United States farm prices[6] would cost around 1.05 USD/kg N and around 3.3 USD/kg P, resulting in a total cost of 85-130 billion USD for N storage and around 60 billion USD for P storage. Similarly, storing 0.4 Mg of SOC per hectare can be translated into an equivalent cost of 40 USD for N and around 26 USD for P (US farm prices), which is very considerable.

These stored nutrients are not directly available for crop growth and should be seen as a long-term investment in environmental and agro-ecological quality. Furthermore, the significant greenhouse gas emissions resulting from chemical fertilizer production and additional emissions of N_2O should be taken into account (West and Marland, 2002a,b; Powlson *et al.*, 2011). Sources other than chemical fertilizers (plant and animal residues and legumes) may provide part of the nutrients needed. If this is the case, their sequestration can be considered as a net capital gain to be included in cost calculations. Currently, however, many agricultural systems in developing countries, especially in Sub-Saharan Africa, suffer from strong nutrient depletion (Bationo *et al.*, 2007). Efficient SOC storage will therefore require a drastic turnaround of the nutrient balance of such systems, as not only does the N removed during harvesting need to be compensated for but extra N is also necessary for SOC storage.

Quantifying the value of the SOC capital stored in the soil is difficult. Sparling *et al.* (2006) showed that the effect of SOC deficiencies (related to previous intensive land use) had only relatively minor effects on pasture production in New Zealand (410 to 990 USD per hectare cumulated over 36-125 years). These impacts on agricultural production were far less than the hypothetical net current values of the extra organic matter stored, which were estimated to vary between 1050 USD and around 8600 USD (2003) in the same period, depending on the C prices and discount rates used.

The wide range of these estimates highlights that calculating SOC sequestration benefits is highly uncertain, as SOC sequestration takes place over decadal to even centennial time scales and economic development over such timescales is impossible to predict accurately. The analysis carried out by Sparling *et al.* (2006), however, foregoes the economic aspects related to a change in agricultural system that are not directly related to SOC

"Harvesting Crops in India"
Photo: World Bank Photo Collection © Curt Carnmark

sequestration, such as investment in new equipment or infrastructure, transaction and evaluation costs related to SOC sequestration contracts, and multiple benefits (or losses) in terms of greenhouse gas emission equivalent that may arise.

Grace *et al*. (2012) carried out a fully integrated economic analysis of SOC sequestration in the Indo-Gangetic plain. They used the methodology proposed by the IPCC (IPCC, 2006) to assess changes in SOC stocks due to conversion from conventional tillage to no-till. Predicted sequestration rates varied between ca. 0.18 and 0.4 Mg C ha^{-1} yr^{-1} over a 20-year period. Their simulations show that C prices need to be significant before a transition targeting only revenues from carbon trading would gain momentum: at a price of 100 USD/Mg, only 17.7% of the total sequestration potential would be achieved. (Lipper *et al*., 2010)) mention similar monetary amounts to compensate for the opportunity costs incurred by farmers not converting rangeland to cropland in West Africa. Considerable uncertainties are associated with these calculations, notably the predicted sequestration rates under alternative management and transaction costs. Nevertheless, it can safely be concluded that these prices are considerably higher than those currently paid at voluntary C trade markets, which are well below 5 USD/Mg^{-1} C^{-1} (Lipper *et al*., 2010), making it clear that strategies focusing on SOC sequestration should also bring other benefits to farmers in order to be viable.

It is interesting to compare these figures with what may be achieved through other strategies. Kindermann *et al*. (2008) made global estimates of the amount of C emissions that could be avoided by reducing deforestation, based on three different models. A reduction of 10% in predicted deforestation could be achieved at a C price between 1.4 and 4.6 USD/Mg (regional prices vary considerably, with the lowest prices in Africa). Such a reduction would be equivalent to the sequestration of 0.09 to 0.12 Pg C y^{-1}. These figures can be compared to the financial effort that might be necessary to achieve a similar result by stimulating sequestration in cropland soils. According to Grace *et al*. (2012), we may assume that 17.7% of the cropland sequestration potential could be achieved at a C price of 100 USD/Mg.

Furthermore, the maximum sequestration rate on cropland is estimated at 0.4 Mg C ha^{-1} yr^{-1} . This implies that global croplands (ca. 15 million km^2) would sequester 0.11 Pg C/year at a cost of 100 USD Mg^{-1} C^{-1}, 20-50 times higher than that necessary to reach a similar goal through forest protection. According to Kindermann *et al*. (2008), even a 50% reduction of deforestation could be achieved at C prices well below 100 USD (35-62 USD Mg^{-1} C^{-1}).

While these cost estimates are grossly oversimplified, they strongly suggest that SOC management in cropland may require much higher investments than strategies avoiding deforestation. This does not have to lead to a conflict situation. Sparing forests will indirectly stimulate better management of existing cropland and higher crop yields, which could result in higher biomass inputs and therefore additional SOC sequestration on the cropland. The costs of sequestering carbon on agricultural land can also be compared with those of CO_2 capture and storage, which were recently estimated at around 300 USD Mg^1C^{-1} for gas-fired plants and around 200 USD Mg^1C^{-1} for coal-fired ones (Finkenrath, 2011). SOC storage may therefore be competitive with this type of mitigation technology.

TOWARD A VISION OF SOC MANAGEMENT

From the foregoing discussion of aspects of SOC dynamics and how they relate to the objectives of the GEF, the following principles are identified, that could guide the GEF in constructing a vision for SOC management that delivers multiple benefits at global and local scales:

SOC management requires an integrated, landscape scale approach, taking a systems view. Only if such an approach is used can the interactions (trade-offs, as well as benefits) of the various components of land use systems be accounted for (Tomich *et al*., 2011). Studies focusing on SOC management related to a single component of the system, such as arable land, may lead to erroneous conclusions if externalities are not accounted for, as compensatory effects may surpass the observed effects. Compensating for a reduction in cropland yields through further extension of

"Woman Plowing Soil" Photo: World Bank Photo Collection. © Ray Witlin

the arable land area is an obvious example. If implementing no-till leads to a modest gain in local SOC stocks but significantly reduces yields at the same time, the overall effect on SOC stocks may be negative as more land will be needed to grow the same crops (De Sanctis *et al*., 2012).

However, interactions are often more subtle. For example, Bationo *et al*. (2007) state that in West Africa up to 30 hectares of dry season grazing may be necessary in order to produce the manure necessary to maintain the fertility of 1 ha of cropland. Promoting the use of manure could therefore increase grazing pressure and the degradation of SOC stocks on the grazing land, as well as further reducing the amount of crop residues that could be directly applied to the cropland. For a correct assessment of the potential benefits of a particular management strategy, the fluxes and stores of organic matter within the whole system being considered need to be accounted for.

SOC management needs to be adapted to local climate, soil and agricultural conditions. There is no one-size-fits-all solution for SOC management. Optimal strategies depend on local conditions simply because these conditions strongly affect SOC dynamics. Therefore, these conditions and the status of SOC stocks need to be carefully assessed before changes in land management are proposed.

SOC is easier (and probably cheaper) to preserve than to restore. While it is desirable to try to restore degraded environments, it is even more important to prevent further degradation. The benefits of protection may seem obvious from a scientific perspective, but protection is not easy to achieve. The development of strategies leading to the incorporation of protection in the livelihoods of local people – rather than as something they experience as being imposed on them – is a great challenge. In some cases, this challenge may only be overcome through substantial financial stimuli to compensate for opportunity costs (Lipper *et al*., 2010).

Improving crop yields and restoring soil fertility through judicious application of nutrients from chemical fertilizers, green manure, compost, amendments (e.g. biochar), ash, farmyard manure or a combination (together with integrated pest management and soil moisture conservation) is a main component of sound SOC management. Organic matter is in demand for other uses such as firewood and charcoal; therefore, realistic goals for its use in agriculture should be set that can be achieved within the setting of resource-poor farming households. Crop productivity should always be a key evaluation criterion when considering management alternatives for arable land or within mixed systems. Two important negative effects of low productivity are: local SOC stocks will be lower; and more land will be needed for production, thereby decreasing natural stocks. Higher SOC stocks are as much an indicator of sound land management as a prerequisite for improved agricultural productivity.

"A woman smiles as she carries a bundle of corn on her back in Nepal." Photo: World Bank Collection © Aisha Faquir

Two examples illustrate the importance of carefully considering the impact of management options on yields. Sileshi *et al*. (2008) carried out a meta-analysis of maize crop yield responses to alternative management systems in West Africa. The systems were based on the use of woody legumes alternated with maize or herbaceous legumes grown as rotational fallows (for a full year) or as relay intercrops (for a short period between crops). All these techniques resulted in increased yields in the year the maize crop was grown. However, use of a rotational fallow or woody legumes means that maize can only be grown every other year at a maximum. The average yield response rate for all treatments was, however, *always less than 2*. This implies a net loss in total maize production compared with the traditional system. The average response rate in the case of full fertilization, on the other hand, was around 3.2.

Bayala *et al*. (2012) carried out a meta-analysis of all grain yields in West Africa under alternative management systems. The average response to the introduction of green manure, soil conservation measures, coppicing trees and the introduction of parkland trees was moderately positive, with average yield in creases of up to 0.5 t ha^{-1}. But maize responded on average strongly negatively to the introduction of parkland trees (-0.4 t ha^{-1}). Implementing such systems in an area where maize is the main staple crop may therefore have unexpected negative effects. The need to increase yields on existing arable land is especially pressing in the tropics, where additional land clearance releases around 120 Mg C ha^{-1} to the atmosphere while only 60-70 Mg C is released for every hectare cleared in other climatic zones (West *et al*., 2010).

Soils and environments should be carefully targeted. It is difficult to achieve substantial gains in agricultural productivity and SOC storage under well-managed, productive systems where residues are already recycled. In these systems the main objective should be to maintain SOC storage and agricultural productivity. Degraded systems with sufficient potential for restoration offer far more potential to achieve relatively rapid gains in crop yield/biomass production and a corresponding increase in SOC when the degraded land is reclaimed for agriculture (Lipper *et al*., 2010; Bayala *et al*., 2012) or converted to forest (Laganiere *et al*., 2010). Assessing the extent to which the soil's actual SOC content is below the potential SOC content (Hassink, 1997), and whether aggregation is still sufficient to allow additional SOC storage, may help set realistic targets. The concept of the manageable range of SOC – which is largely a function of soil texture (Verheijen *et al*., 2005) – could be helpful in this regard.

Appropriate diagnostic tools that use soil fractionation and/or rapid, non-destructive sensing techniques may facilitate the matching of soils with suitable management approaches. Similarly, when new agricultural land is needed (which will probably be the case in Sub-Saharan Africa), SOC loss may be reduced if the most suitable areas for conversion are carefully selected. Injudicious replacement of natural vegetation by forests may not only lead to adverse corollary effects such as a decrease in water yield (Buytaert *et al*., 2002) but may also cause a net *decrease* in SOC stocks related to hydrological changes induced by tree planting. In particular, grasslands in wetter regions tend to lose considerable amounts of soil carbon when they are afforested (Farley *et al*., 2004; Berthrong *et al*., 2012), thereby partially or totally offsetting gains in biomass C.

Realistic goals should be set. After initial enthusiasm, it is now clear that even the best alternative management techniques may allow at best modest gains in SOC stocks, depending on local climatic conditions, soil type, topography and the management system in place. Recent research suggests that global SOC gains (through management) possibly exceeding 1 Pg yr^{-1} on cropland alone, as was suggested some years ago (Paustian *et al*., 1997; Lal, 2004, 2010), appear to have been overly optimistic. These gains correspond to an annual sequestration rate of 0.6 Mg C ha^{-1} yr^{-1} *on all cropland in the world*. Experimental data suggest that this rate may be obtained locally (under the best possible conditions) for several decades, but regional surveys show that this is not globally achievable (Christopher *et al*., 2009). Other management techniques aimed at increasing SOC stocks have similar limitations.

It should also be noted that sequestration rates cannot be stacked, i.e. we cannot "double dip" by converting degraded cropland into forests and implementing no-till and agroforestry there at the same time. However, it is reasonable to hypothesize that suitable management strategies can be found for different biophysical and socio-economic conditions which will result in positive SOC responses. Sustainability models that help to decide which site-adapted management strategy will produce the greatest SOC benefits are still lacking.

Carbon sequestration can generate multiple benefits. SOC storage is still not economically viable in most cases (see above). Improving it may therefore rely on the generation of co-benefits. These benefits may be related to increases in yield (through better fertilizer management and intensification), reduced labor (through concentrating crop production in a smaller area) or biodiversity conservation (Bekessy and Wintle, 2008).

Socio-economic conditions that affect the potential success of SOC management projects should be assessed. Lipper *et al.* (2010) and Stringer (2012) describe various socio-economic hurdles that can hamper successful implementation of sustainable land projects in an African context (e.g. highly fragmented land use, poorly defined ownership structures, absence of extension services, high transaction costs and monitoring costs). More research is needed to identify strategies that could work in any of the multitude of local societal contexts. This will require a pragmatic approach, focusing the collection of evidence on what works and what does not (and the reasons) rather than top-down reasoning based upon a (too) idealistic theoretical framework (Banerjee and Duflo, 2011).

The socio-economic implications of changes in land management should be assessed. Giller *et al.* (2009) point out that changes in agricultural management systems may not only lead to an increased overall workload (weeding, cutting etc.) but may also shift the gender balance in regard to this workload toward women. While changes are unavoidable, we should strive to avoid undesirable ones, while proposed practices should be compatible with local culture (Stringer *et al.*, 2012).

Account should be taken of the biophysical (e.g. drought) and socio-economic and institutional risks (e.g. labor, access to inputs) inherent in the environment where a project is located. Smallholder farmers in developing countries are risk-averse out of necessity. Their income and capital basis does not allow them to aim for major gains if such a strategy involves significant risk. Projects may focus on reducing the inherent risk, e.g. by providing supplemental irrigation to overcome droughts (Rockström *et al.*, 2003). Alternatively, strategies need to be developed wherein the risk is accepted and accounted for within the project design, e.g. by reinforcing existing coping strategies. A broad mindset is needed here, so that all possibilities are considered, including public interventions that used to be dismissed because of their "market distorting" nature (Devereux, 2001).

Adequate project support systems need to be provided. The response time of SOC stocks to a management or land use change will be at least several decades. Immediate returns to the local community will therefore be small and may even be hard to detect. This drawback can only be overcome if co-benefits, such as yield increases, can be generated and/or sufficient support can be provided over a sufficiently long time span. This will not be easy, given the (short-term) opportunity costs that may be involved (Lipper *et al.*, 2010). A carefully designed strategy covering several decades is required.

Where possible, novel, high-throughput monitoring techniques should be used, in combination with an appropriate modeling framework. The implementation of novel monitoring techniques is essential to collect more data on SOC inventories, often at a fraction of the price of more classical methods (Grunwald *et al.*, 2011). Current models may not always be able to correctly predict the magnitude of changes in SOC stocks measured over relatively short time spans. Nevertheless, the use of a modeling framework is essential even if this is the case. Use of a properly calibrated model will allow predicting the order of magnitude of change in SOC stocks that can be expected when a program is implemented. Moreover, by comparing observed changes with model predictions, important factors may be identified that are missing or not well represented within the modeling framework being used. This will allow correctly targeting areas where further research is needed.


"Women show their agricultural products, India" Photo: World Bank Photo Collection © Simone D. McCourtie


Photo: iStockphoto © Robert Dodge

CONCLUSIONS AND RECOMMENDATIONS

Our knowledge of SOC and SOC dynamics has grown considerably in the last two decades as the importance of sequestering carbon for climate mitigation purposes has been appreciated. Major progress has been made in understanding the overall controls on SOC dynamics and SOC chemistry (see Section 3). SOC monitoring now benefits considerably from remote sensing techniques developed in recent years (see Section 5,"SOC monitoring"). However, the increase in our knowledge has merely confirmed that SOC dynamics are difficult to assess and to predict, not only because SOC is complex in itself (Schmidt *et al.*, 2011) but also because the inter-relationships between SOC and its controls are complicated (Heimann and Reichstein, 2008). Increased knowledge can therefore rarely be directly translated into straightforward SOC management rules: rather, it will contribute to our understanding of a complex system whose response is inherently difficult to predict. As Goethe wrote: "Mit dem Wissen wächst der Zweifel" ("With increasing knowledge comes more doubt").

Thus, while we need to improve our understanding so that our conceptual description of SOC dynamics will become more mechanistic, further developing our scientific knowledge is not in itself a strategy that will automatically result in more effective SOC ***management strategies. Issues – other than lack of knowledge – which may hamper efficient SOC management***, *such as local socio-economic context and inadequate project support systems,* ***also need to be considered when developing strategies for SOC management*** (see Section 5).

Nevertheless, some areas of research on SOC warrant specific attention. One is ***the response of SOC to climate change.*** While we know that SOC dynamics are responsive to environmental changes, we do not have sufficient knowledge of the climate sensitivity of SOC to predict confidently its response to climate warming and/or changes in the hydrological regime. Uncertainty about the fate of the global SOC stocks over the next century is truly dramatic. The simulations evaluated by Eglin *et al.*, 2010 vary from an increase of 300 Pg C to a decrease of 50 Pg C. This uncertainty is of the same order of magnitude as the total amount of soil C released from the SOC reservoir to the atmosphere during the whole Holocene!

The main reason why the response of SOC to climate change is crucial is that major changes in the SOC reservoir could themselves have a potential impact on global climate. However, the question is also important with respect to evaluating the efficacy of any SOC management strategies, as it implies that the baseline against which effects are measured may change over the same time scale and at a similar magnitude as the effects that need to be assessed. Not only does correctly assessing the effect of climate change on SOC mineralization require good insight into the mechanisms that control the temperature sensitivity of SOM decomposition (e.g. by measuring Q_{10} values), but it may be even more important to understand better how the environmental constraints on SOM decomposition change with changing climate (Davidson and Janssens, 2006).

A recent review by Conant *et al*. (2011) of the relationship between temperature and SOM decomposition rates highlights our ignorance on this topic. They found that laboratory studies generally show that the decomposition rate of SOM is indeed temperature-dependent and that, in agreement with kinetic theory, the temperature response is more important for less decomposable carbon substrates. However, interpreting the results of field studies

on temperature response is often difficult because carbon pools with different rates of decomposition cannot be isolated.

A major shortcoming of existing studies identified by Conant *et al*. (2011) is that most of these studies focus on SOM pools with a relatively short turnover time. Information on the response of the SOM pools with turnover times of decades or more – which are likely to be most important for understanding the overall SOC response to climate change – is almost completely lacking. As this problem cannot be resolved by providing more information of the same nature through incubation and/or field experiments, they propose re-orienting research toward the response of specific processes that control SOM dynamics to temperature change, using a new conceptual model as a guiding framework. While this would undoubtedly allow important steps forward in our scientific understanding, it also creates a new problem since a more complex, process-based model such as this can only be made operational if a large number of state variables and parameter values are known.

A second area that needs attention is ***further evaluation of the "saturation" concept***. Determining whether a soil is under- or oversaturated with C may have profound effects with respect to the management strategies that may be developed. In areas where soils are undersaturated, significant gains in SOC storage may result from improved management or conversion to a more suitable land use. If, on the other hand, the soil system is saturated or oversaturated, gains may be much less important or even impossible. While the saturation concept has been around for some two decades, the criteria used to determine the saturation level of a soil are still only approximately known (e.g. depending only on the soil's clay content, and not accounting for differences in soil mineralogy and/or potential effects that climate and hydrology may have on the saturation level that might be achieved) (Angers *et al*., 2011).

A third area where a thorough examination is indicated is ***how SOC monitoring may be improved in the future***. Credible, certifiable reporting of SOC stocks is essential if SOC sequestration is to become a significant part of global mitigation efforts. Assessing the evolution of SOC stocks critically depends on adequate monitoring of these stocks: given that the rate of change in SOC stocks is relatively low (as compared to the total inventory), very accurate SOC information is needed in order to assess changes over relatively short timescales (e.g. five years). Assuming, for example, that implementation of an alternative management technique results in a sequestration rate of 0.5 Mg C ha^{-1} y^{-1}, the total C stock of a typical cropland will change by only 0.5-2% (relative to the existing stock) over a five-year period. These relatively small changes may be one reason studies fail to detect differences between management techniques (type II errors). Traditional methods may be complemented by novel high-throughput techniques not only to increase accuracy, but also to allow better spatial coverage (Leone *et al*., 2012; McDowell *et al*., 2012; Stevens *et al*., 2012).

Even if more rapid and economical techniques for assessing SOC stocks are used, relatively small differences may still be undetectable. Thus, while monitoring should be a key component of any SOC management initiative, the use of models will provide complementary information, allowing the main controls that are altered by a change in management/land use to be identified and meaningful spatial extrapolations to be made. It is therefore important to ***consider how models and monitoring can be better integrated with the evaluation of alternative SOC management practices***.

A good basis for further progress is the existing GEFSOC modeling framework (Easter *et al*., 2007; Milne *et al*., 2007). The GEFSOC applies two well-established SOC models (Century and Roth-C) as well as the empirical IPCC method for SOC context within a GIS environment, so that spatial variations in controlling factors can be explicitly accounted for. More details can be found in Easter *et al*. (2007). The model has already been used to predict effects of land use and/or climate change in four test areas located in Jordan (Al-Adamat *et al*., 2007), India (Bhattacharyya *et al*., 2007), Kenya (Kamoni *et al*., 2007) and Brazil (Cerri *et al*., 2007).

Several strategies could improve such a spatially explicit modeling system (see also Grunwald *et al*., 2011):

(i) The quality and quantity of the input data can be improved, e.g. by providing additional information through remote sensing. This is important not only in regard to SOC, but also to ancillary data such as geology and topography.

(ii) The carbon models themselves may be improved, e.g. by accounting explicitly for factors hitherto not incorporated (soil mineralogy) or by better describing the temperature sensitivity of various pools of SOC.

(iii) Landscape scale models should account not only for vertical exchanges between plants, soil and atmosphere, but also for lateral fluxes such as those induced by soil erosion (Van Oost *et al*., 2007) or export of dissolved organic carbon (DOC, Aitkenhead and McDowell, 2000).

(iv) Interpolation methods may be optimized to make optimal use of covariates of SOC.

The issues discussed above are only the most pressing scientific questions relevant to SOC management. Further research on soil biodiversity, its role in the soil and how it supports both soil health and productivity has also been identified as an important addition to our knowledge, which the GEF may consider as a targeted research project. A detailed overview of open scientific issues with respect to SOC dynamics in general can be found in Stockmann *et al*. (2013).

Several issues other than lack of scientific knowledge hamper the use of improved strategies for SOC management that could be implemented using current scientific understanding. The GEF should therefore give considerable attention to ***how, with the present state of knowledge, we can advance the implementation of optimal SOC management in various agro-ecological systems***. A series of guidelines and principles that may be discussed has been proposed in this publication in order to stimulate further investigation. Nevertheless, the evidence to date for identifying soil organic carbon management as a powerful entry point for delivering global environmental and developmental benefits is compelling and is certainly worth pursuing further.

"Farmer in Brazil"
Photo: World Bank Photo Collection © Yosef Haddar

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