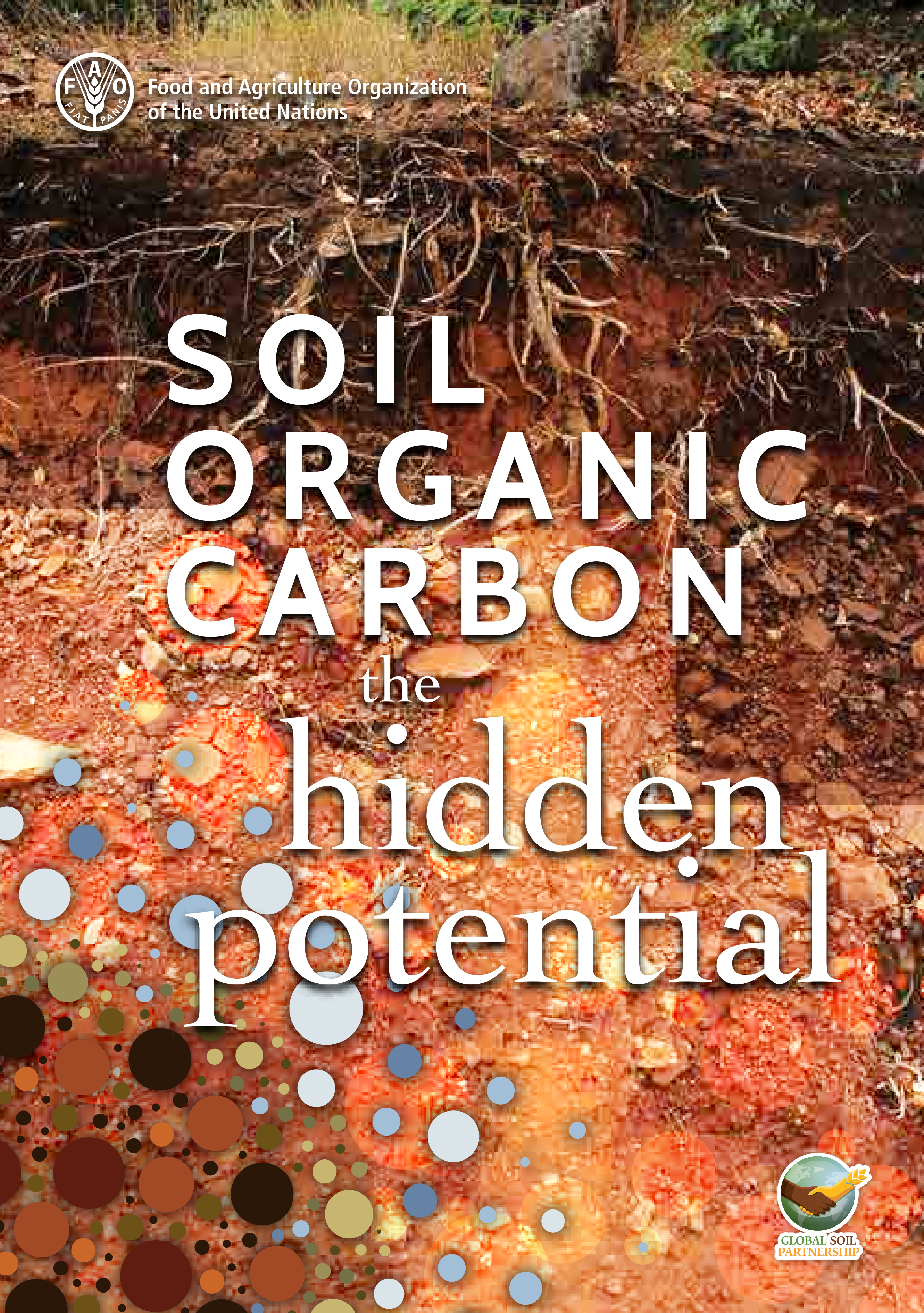

Food and Agriculture Organization
of the United Nations

SOIL ORGANIC CARBON

the hidden potential

GLOBAL SOIL
PARTNERSHIP

SOIL ORGANIC CARBON

the hidden potential

AUTHORS

Lefèvre Clara (FAO)
Rekik Fatma (FAO)
Alcantara Viridiana (FAO)
Wiese Liesl (FAO)

EDITORS

Wiese Liesl (FAO)
Alcantara Viridiana (FAO)
Baritz Rainer (FAO)
Vargas Ronald (FAO)

REVIEWERS

Federici Sandro (FAO)
Taboada Miguel (INTA, Argentina)
Cuevas Rosa (REDLABS, Mexico)
Montanarella Luca (European Commission)

DESIGN & PUBLICATION

Sala Matteo (FAO)
Verbeke Isabelle (FAO)
Stanco Giulia (FAO)

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EXECUTIVE SUMMARY

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

After carbon enters the soil in the form of organic material from soil fauna and flora, it can persist in the soil for decades, centuries or even millennia. Eventually, SOC can be lost as CO_2 or CH_4 emitted back into the atmosphere, eroded soil material, or dissolved organic carbon washed into rivers and oceans. The dynamics of these processes highlight the importance of quantifying global carbon fluxes to ensure maximum benefits of SOC to human well-being, food production, and water and climate regulation.

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

Globally, SOC stocks are estimated at an average of 1 500 PgC in the first meter of soil, although their distribution is spatially and temporally variable. SOC hot-spots and bright spots, which are respectively areas of high SOC content (e.g. peatlands or black soils) and large surface areas of low SOC content (e.g. drylands) constitute major zones of concern. With climate change and unsustainable management, these areas are likely to become net sources of GHG emissions. However, if managed wisely, they have the potential to sequester large amounts of carbon in their soils, thus contributing to climate change mitigation and adaptation.

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

Climate change poses a major threat to food security through its strong impact on agriculture. It is thought to negatively affect crop, livestock and fishery production through yield reductions, biological migration and loss of ecosystem services, which ultimately lead to a reduction in agricultural incomes and an increase in food prices. SOC sequestration can support the mitigation of these issues while offering part of the solution to a warming climate. Therefore, a number of suggested SOC conserving practices need to be implemented in order to reach the maximum potential of climate change mitigation and adaptation and food productivity. However, a number of barriers to adopting these practices exist, including financial, technical/logistical, institutional, knowledge, resource and socio-cultural barriers and their interactions. When these barriers are combined with abiotic factors which restrict SOC build-up, they prevent the adoption of climate change mitigation and adaptation practices. Despite some recognized solutions to overcome human induced barriers, global adoption rates of sustainable soil management practices remain relatively low.

This publication aims to provide an overview to decision-makers and practitioners of the main scientific facts and information regarding the current knowledge and knowledge gaps on SOC. It highlights how better information and good practices may be implemented to support ending hunger, adapting to and mitigating climate change and achieving overall sustainable development.

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ACRONYMS

AFOLU	Agriculture, Forestry and Other Land-Use
AR	Assessment Report of the IPCC
BD	Bulk density
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
COP	Conference of the Parties of the UNFCCC
DOC	Dissolved organic carbon
GHG(s)	Greenhouse gas(es)
GPD	Global Peatland Database
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
ITPS	Intergovernmental Technical Panel on Soils
KP	Kyoto Protocol
LU	Land use
LUC	Land use change
MRV	Measurement/monitoring, reporting and verification
N_2O	Nitrous oxide
NDC	Nationally Determined Contributions
NPP	Net primary productivity
QA/QC	Quality assurance/quality control
PgC	Petagrams of carbon[1]
SMN	Soil Monitoring Network
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Sub-Saharan Africa
UNCBD	United Nations Convention on Biological Diversity
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
Vis-NIR	Visible-near infrared
WMO	World Meteorological Organization
WRB	World Reference Base

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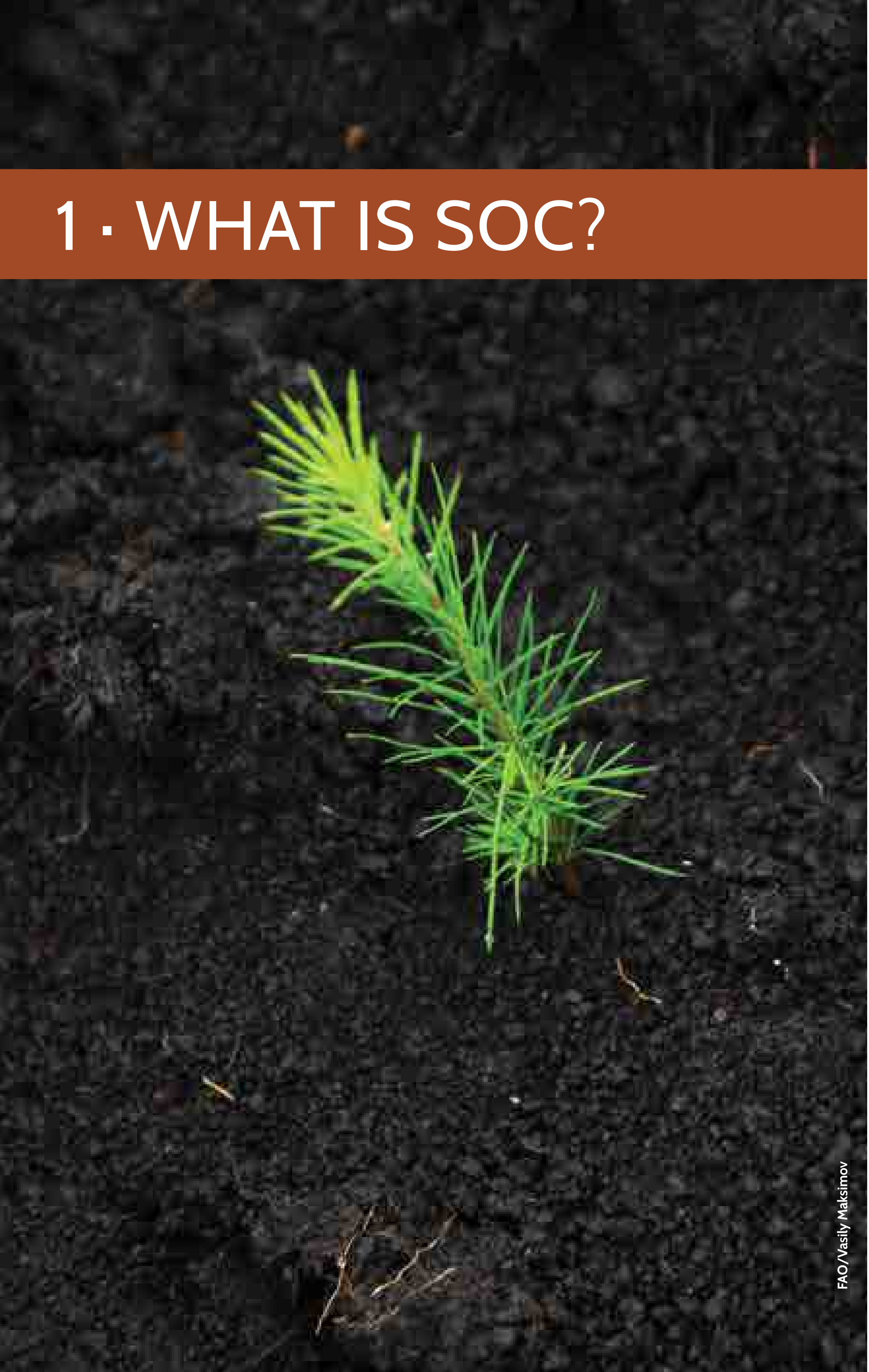
[1] 1 PgC = one billion metric tonnes of carbon = 3.7 billion tonnes of CO_2 = 1 GtC (gigaton of carbon)

1 · WHAT IS SOC?



FAO/Vasily Maksimov

1.1 · SOC: A CRUCIAL PART OF THE GLOBAL CARBON CYCLE

Soil organic carbon (SOC) is one part in the much larger global carbon cycle that involves the cycling of carbon through the soil, vegetation, ocean and the atmosphere (Figure 1). The SOC pool stores an estimated 1 500 PgC in the first meter of soil, which is more carbon than is contained in the atmosphere (roughly 800 PgC) and terrestrial vegetation (500 PgC) combined (FAO and ITPS, 2015) (See section 3.1 for more information on SOC stocks). This phenomenal SOC reservoir is not static, but is constantly cycling between the different global carbon pools in various molecular forms (Kane, 2015).

While CO_2 (carbon dioxide) and CH_4 (methane) are the main carbon-based atmospheric gases, autotrophic organisms (mainly plants), as well as photo- and chemo-autotrophic microbes synthesize atmospheric CO_2 into organic material. Dead organic material (mainly in the form of plant residues and exudates) is incorporated into the soil by soil fauna, leading to carbon inputs into the soil through organic material transformation by heterotrophic microorganisms. This organic material transformation process results in a complex biogeochemical mixture of plant litter compounds and microbial decomposition products in various stages of decomposition (Von Lützow *et al.*, 2006; Paul, 2014) that can be associated with soil minerals and occluded within aggregates, enabling SOC persistence in soil for decades, centuries or even millennia (Schmidt *et al.*, 2011). CO_2 is emitted back into the atmosphere when soil organic matter (SOM) is decomposed (or mineralized) by microorganisms. Carbon loss can also be caused by root exudates such as oxalic acid, which liberate organic compounds from protective mineral associations (Keiluweit *et al.*, 2015). Finally, carbon is also partly exported from soils to rivers and oceans as dissolved organic carbon (DOC) or as part of erosion material.

In principle, the amount of SOC stored in a given soil is dependent on the equilibrium between the amount of C entering the soil and the amount of C leaving the soil as carbon-based respiration gases resulting from microbial mineralization and, to a lesser extent, leaching from the soil as DOC. Locally, C can also be lost or gained through soil erosion or deposition, leading to the redistribution of soil C at local, landscape and regional scales. Levels of SOC storage are therefore mainly controlled by managing the amount and type of organic residues that enter the soil (i.e. the input of organic C to the soil system) and minimizing the soil C losses (FAO and ITPS, 2015).

Factors controlling the decomposition of organic matter in soil include soil temperature and water content (mainly determined by climatic conditions) which greatly influence soil C storage through their effect on microbial activity. The composition of the microbial community (e.g. the bacteria:fungi ratio) may also have an influence on the preferential decomposition of certain compounds. The presumed chemical recalcitrance of complex molecules that build up SOC, such as lignin or lipids, does not substantially contribute

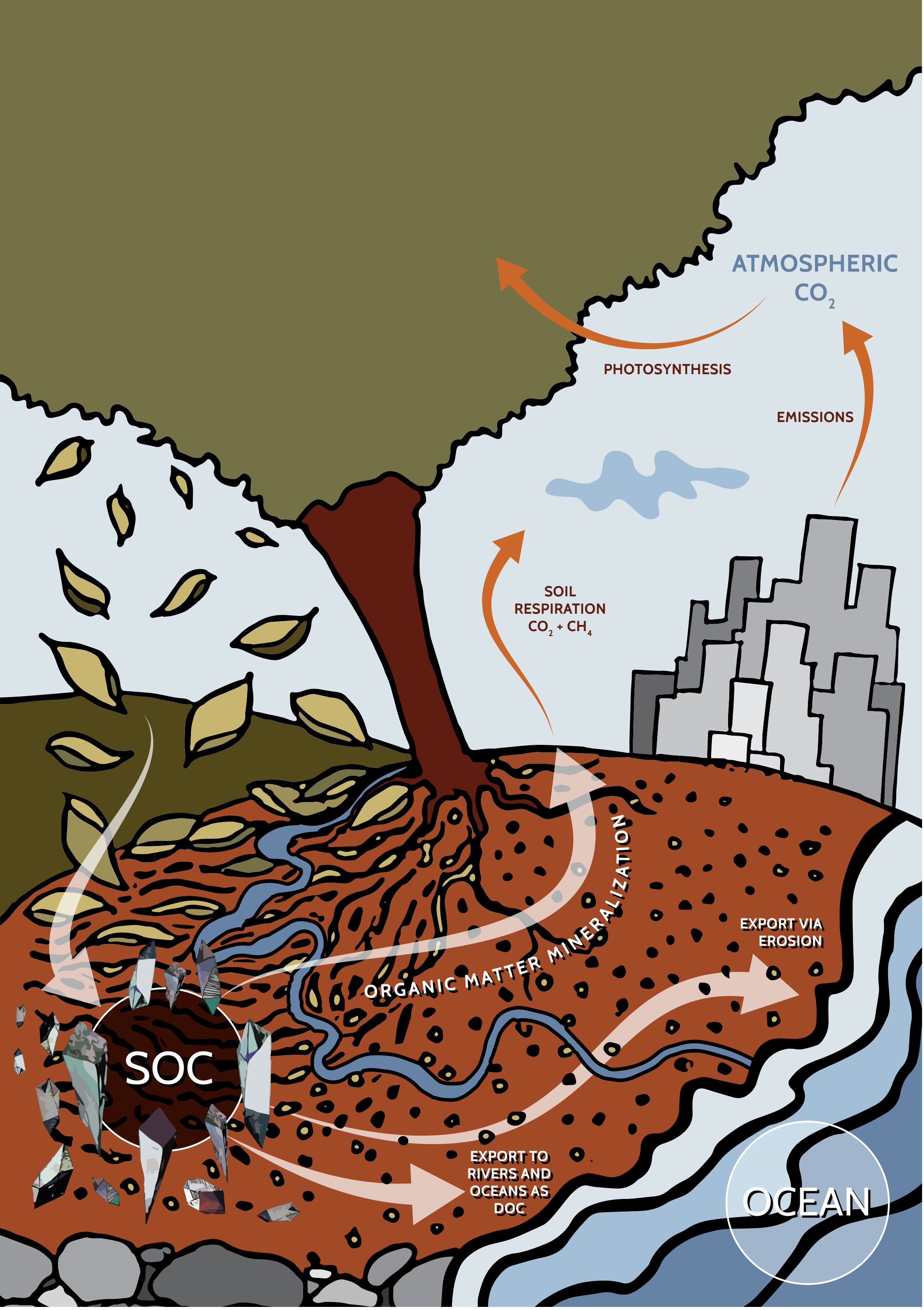


Figure 1 · SOC in the global carbon cycle.

to SOM persistence in soil (Marschner *et al.*, 2008; Thévenot *et al.*, 2010). SOM persistence is rather affected by SOC stabilization in the soil matrix through its interaction and association with soil minerals (Schmidt *et al.*, 2011).

The quantification of global carbon fluxes is necessary to clarify, amongst others, whether global terrestrial ecosystems fix more atmospheric CO_2 via photosynthesis than they return to the atmosphere through respiration. On the one hand, the global carbon budget is determined by the atmospheric CO_2 concentration and the uptake of CO_2 by the ocean and the land and, on the other hand, by the emissions derived from fossil fuel emissions, land use and land use change. The most recent C assessment indicated that, between 2006 and 2015, fluxes from land to the atmosphere were twice as high as the sum of the ocean and land sinks, with 90 percent of these emissions originating from fossil fuels and industry (Le Quéré *et al.*, 2016). The carbon flux derived from land use changes was more predominant in preindustrial times since, between 1750 and 2011, one-third of all anthropogenic greenhouse gases (GHGs) was derived from land use changes (IPCC, 2014). On a long-term basis, atmospheric CO_2 has increased from about 180 to 280 ppm since the last glacial period, adding about 220 PgC to the atmosphere over a 10 000-year period. This translates to a rate of increase of about 4.4 PgC/year (Baldocchi *et al.*, 2016).

Recent research on soil C dynamics and its influence on the global carbon cycle has been driven in part by increasing awareness of: 1) the importance of small scale accessibility to SOC for microbial carbon turnover that extends in dimension beyond a depth of 20 cm depth (Trumbore and Czimczik, 2008; Schimel and Schaeffer, 2012; Vogel *et al.*, 2014); 2) the link between microbial communities and the dynamic and inherent soil properties in relation to the carbon cycle and its interaction with other biogeochemical cycles (Trumbore and Czimczik, 2008; Gärdenäs *et al.*, 2011); and 3) the influence of plant diversity in increasing soil microbial activity and soil carbon storage (Lange *et al.*, 2015).

1.2 · SOC: A COMPONENT OF SOM

The term SOM is used to describe the organic constituents in soil in various stages of decomposition such as tissues from dead plants and animals, materials less than 2 mm in size, and soil organisms. SOM turnover plays a crucial role in soil ecosystem functioning and global warming (See also section 2.1). SOM is critical for the stabilization of soil structure, retention and release of plant nutrients and maintenance of water-holding capacity, thus making it a key indicator not only for agricultural productivity, but also environmental resilience. The decomposition of SOM further releases mineral nutrients, thereby making them available for plant growth (Van der Wal and de Boer, 2017), while better plant growth and higher productivity contribute to ensuring food security.

SOM can be divided into different pools based on the time needed for full decomposition and the derived residence time of the products in the soil (turnover time) as follows (Gougoulias *et al.*, 2014):

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

Long turnover times of organic compounds are not only explained by anaerobic conditions such as in peats, but also by incorporation of SOM components into soil aggregates, attachment of organic matter to protective mineral surfaces, the spatial disconnection between SOM and decomposers and the intrinsic biochemical properties of SOM. Microaggregates are considered responsible for the stabilization of the passive pools (permanent stabilizing agents), whereas macroaggregates and clods encapsulating small aggregates (Degens, 1997) are considered transient stabilizing agents (Tisdall and Oades, 1982; Dexter, 1988). This physical and chemical stabilization of SOM hinders, to different degrees, microbial decomposition via restricted mobility and access of microbes to organic matter, as well as diffusion of water, enzymes and oxygen. In addition, such stabilization requires a broad range of microbial enzymes to degrade the insoluble macromolecules that comprise SOM (Van der Wal and de Boer, 2017).

SOM contains roughly 55–60 percent C by mass. In many soils, this C comprises most or all of the C stock – referred to as SOC – except where inorganic forms of soil C occur (FAO and ITPS, 2015). Similar to SOM, SOC is divided into different pools as a function of its physical and chemical stability (FAO and ITPS, 2015; O'Rourke *et al.*, 2015):

- **Fast pool** (labile or active pool) - After addition of fresh organic carbon to the soil, decomposition results in a large proportion of the initial biomass being lost in 1–2 years.
- **Intermediate pool** - Comprises microbially processed organic carbon that is partially stabilized on mineral surfaces and/or protected within aggregates, with turnover times in the range 10-100 years.
- **Slow pool** (refractory or stable pool) - highly stabilized SOC, enters a period of very slow turnover of 100 to >1 000 years.

An additional slow SOC pool is pyrogenic SOC, formed from partially carbonized (e.g., pyrolyzed) biomass during wildfires (Schmidt and Noack, 2000) which is present in many ecosystems. A portion of this material has a highly condensed aromatic chemical structure (often referred to as pyrogenic carbon or black carbon) that resists microbial degradation and thus persists in soils for long periods (Lehmann *et al.*, 2015).

The separation of SOC into different pools is largely more conceptual than measurable and is based on the ease of SOC oxidation or degree of physical stabilization within aggregates or through attachment to minerals determined through analytical protocols. Although SOC pools are often used to model carbon dynamics, ways to reconcile "measurable" and "modellable" pools have rarely been reported (Zimmermann *et al.*, 2007; Luo *et al.*, 2014). SOC and SOM should therefore also be considered a continuum of organic material in all stages of transformation and decomposition or stabilization (Lehmann and Kleber, 2015).

The proportion of labile SOC to total SOC, rather than the total SOC pool *per se* influences SOC sequestration and soil health (Blair *et al.*, 1995). The labile carbon fraction has been shown to be an indicator of key soil chemical and physical properties. For example, this fraction was found to be the primary factor controlling aggregate breakdown in Ferrosols (non-cracking red clays), measured by the percentage of aggregates measuring less than 0.125 mm in the surface crust after simulated rain in the laboratory (Bell *et al.*, 1998, 1999). The resistant or stable fraction of soil organic carbon contributes mainly to the soil's nutrient holding capacity (cation exchange capacity). Additionally, because this fraction of organic carbon decomposes very slowly, it is especially interesting in terms of long-term SOC sequestration.

1.3 · SOIL: A SOURCE AND SINK FOR CARBON-BASED GHGs

Soil can be a double-edged sword when it comes to carbon fluxes. Anthropogenic impacts on soil can turn it into either a net sink or a net source of GHGs. As a source, soil emits GHGs into the atmosphere where they trap thermal radiation that enhances the greenhouse effect and contributes to global warming. The carbon-based GHGs emitted by soil are CO_2 and methane (CH_4) which are two of the most leading anthropogenically emitted GHGs (IPCC, 2014). Another form of GHG is nitrous oxide (N_2O), the emission of which has become increasingly anthropogenically driven, largely from agricultural soils and livestock facilities. The inclusion of all three gases in soil CO_2 budgets is important due to the interconnectedness of the processes involved in their emissions and ecosystem cycling (carbon-nitrogen, aerobic–anaerobic processes). The potential climate signal of these gases differs depending on their relative greenhouse efficiency, i.e. their global warming potential (GWP). CO_2 is considered to have a GWP of 1, followed by CH_4 with a 100-year GWP of 28 and N_2O with the highest 100-year GWP of 265 (IPCC, 2014).

1.3.1 · CARBON DIOXIDE (CO_2)

Carbon dioxide (CO_2) is the most abundant carbon-based gas in the atmosphere. Prior to the industrial Era, atmospheric CO_2 concentrations fluctuated between 180 and 290 ppm for 2.1 million years (Hönisch *et al.*, 2009). On a cumulative basis, the atmospheric CO_2 increase between 1750 and 2011 was 240 PgC. In 2014, atmospheric CO_2 abundance reached over 397 ppm (Le Quéré *et al.*, 2016) which was 40 percent higher than before industrialization. The increase in atmospheric CO_2 concentration is mainly attributed to the combustion of fossil fuels and land use ch ange, especially deforestation (IPCC, 2014).

In soils, CO_2 release to the atmosphere occurs when organic residues or SOM are oxidized. The flux of respired CO_2 by soil fauna and below-ground roots from the soil to the atmosphere is referred to as soil respiration and it represents the second-largest terrestrial carbon flux (Raich and Potter, 1995). Soil respiration is seasonally variable since it is controlled by environmental factors such as temperature, moisture, soil nutrient content and oxygen concentration. The effect of climate change (particularly rising temperatures and shifting precipitation regimes) on soil respiration is addressed in section 2.3.1.

1.3.2 · METHANE (CH_4)

Based on its GWP, CH_4 is 28 times more potent as a GHG than CO_2 (IPCC, 2007). Methane is released from soils through a process called methanogenesis which occurs during decomposition of organic matter under anaerobic (oxygen depleted) conditions. In such environments, methanogens - the leading form of bacteria that produce methane- in addition to acetate fermentation, utilize CO_2 instead of oxygen as a final electron acceptor for metabolic activities, releasing CH_4 as a by-product. Thus, waterlogged soils, particularly wetlands, peatlands and rice paddies, are the largest source of methane emissions (FAO and ITPS, 2015). In 1998, total global emissions of CH_4 from wetlands were estimated to be 0.15 Pg/year, of which 0.09 Pg/year came from natural wetlands and 0.05 Pg/year from rice paddies. Furthermore, GHG inventories reported that CH_4 emissions from rice paddies were estimated to have increased from 0.37 $PgCO_2$-eq/year in 1961 to 0.50 $PgCO_2$-eq/year in 2010 (FAO and ITPS, 2015).

Contrastingly, soils also have remarkable storage potential of the core constituents of these GHGs (notably C; this process called soil carbon sequestration is discussed in Section 1.4). Under aerobic conditions (or the presence of oxygen), methanotrophic soil bacteria thrive and use methane as a source of carbon in a process called methanotrophy which oxidizes methane. As such, forest soils tend to be good sinks for methane due to their low water table that allows these bacteria to grow (Serrano-Silva *et al.*, 2014). Hence, water table level is considered the key as to whether a soil acts as sink or a source of methane. Nitrogen and temperature are also noted as determinants of a soil's carbon sequestration potential since they regulate the amount of methane emissions (Kane, 2015).

1.4 · SOC SEQUESTRATION

Soil organic carbon sequestration is the process by which carbon is fixed from the atmosphere via plants or organic residues and stored in the soil. When dealing with CO_2, SOC sequestration involves three stages: 1) the removal of CO_2 from the atmosphere via plant photosynthesis; 2) the transfer of carbon from CO_2 to plant biomass; and 3) the transfer of carbon from plant biomass to the soil where it is stored in the form of SOC in the most labile pool. This pool is characterized by the highest turnover rate (days - few years), encompasses recently incorporated plant residues and is readily decomposable by soil fauna, generally causing CO_2 emissions back into the atmosphere (see also section 1.1). Therefore, imperative SOC sequestration action planning requires looking beyond capturing atmospheric CO_2, and necessitates finding ways to retain C in the slow SOC pool. Contrastingly, research shows that the stable pool has a negligible potential for carbon sequestration due to its resistance to change and hence, irresponsiveness to management (Kane, 2015).

Newly added carbon can be stabilized in the soil by a number of mechanisms (Six *et al.*, 2002; Six *et al.*, 2006; Jastrow *et al.*, 2007; Kane, 2015). Physically, carbon may be stabilized via its isolation inside soil micro- and macro aggregates where it is inaccessible to soil organisms. Chemically, carbon may be strongly adsorbed to clays via chemical bonds which prevents the consumption of carbon by organisms. Biochemically, carbon may be re-synthesized into complex molecule structures that may hinder decomposition. The three mechanisms depend on a number of biotic, abiotic and management factors that shape their soil carbon stabilization efficacy (Six *et al.*, 2006; Kane, 2015).

The concept of soil carbon saturation implies that the soil carbon stock has reached its maximum carrying capacity for storing soil carbon inputs (Six *et al.*, 2002; Stewart *et al.*, 2007). This threshold, which depends on many factors including inherent and dynamic soil properties and their interactions with abiotic factors, is also referred to in literature as the maximum carbon stabilization capacity (Beare *et al.*, 2014). It infers that soil carbon stabilization curves are not infinitely increasing, and that when a C saturation level is reached, SOC sequestration comes to an end, soils stop being a net carbon sink and may become a net carbon source. As such, SOC sequestration has spatial and temporal limitations and is a reversible process (Paustian *et al.*, 2016). Soils that are depleted of SOC have the greatest potential to gain carbon, but also have the least propensity to do so. Since the majority of soils around the world are far from their saturation thresholds, there is great potential for increased carbon inputs and management that protects existing stocks to maximize soil carbon sequestration (Kane, 2015).

In general, carbon cycling and carbon sequestration is most active in topsoil horizons, whereas stabilized carbon with longer turnover times makes up a greater proportion of the total SOC found in deep soil horizons (Trumbore, 2009; Rumpel *et al.,* 2012). Beare *et al.*, (2014) estimated that soils at greater depth have a higher capacity of storing additional C compared to topsoils because of a larger difference between the existing SOC content and the SOC saturation value. The accumulation of stabilized C with long residence times in deep soil horizons may be due to continuous transport, temporary immobilization and microbial processing of DOC within the soil profile (Kaiser and Kalbitz, 2012) and/or efficient stabilization of root-derived organic matter within the soil matrix (Rasse *et al.*, 2005). Lorenz and Lal (2005) emphasized that subsoils have the potential to store 760-1520 Pg additional carbon.

At the same time, it was pointed out that care should be taken when adding new C sources to subsoils because of the risk of enhanced mineralization of existing SOC. Nevertheless, increasing SOC stocks in subsoil is still recognized as a promising means to enable substantial C sequestration in soils (Rumpel *et al.*, 2012).

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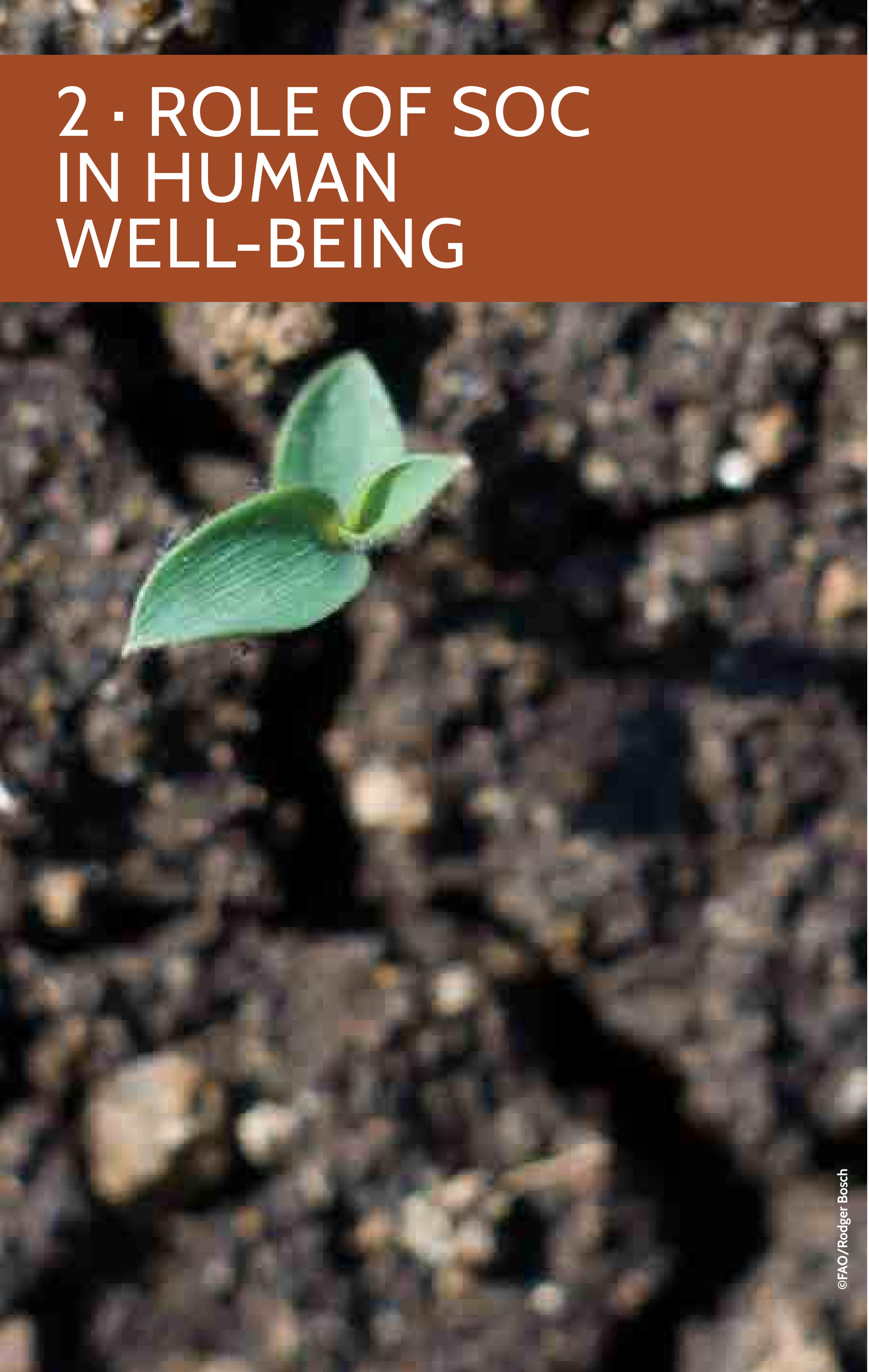
2 · ROLE OF SOC IN HUMAN WELL-BEING



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2.1 · ACHIEVING THE SUSTAINABLE DEVELOPMENT GOALS

As highlighted in the first principle established by the revised World Soil Charter (FAO, 2015a, p.2),

> *"soils are a key enabling resource, central to the creation of a host of goods and services integral to ecosystems and human well-being. The maintenance or enhancement of global soil resources is essential if humanity's overarching need for food, water, and energy security is to be met. In particular, the projected increases in food, fibre, and fuel production required to achieve food and energy security will place increased pressure on the soil".*

The 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development which were adopted by world leaders in September 2015 identified the need to restore degraded soils and improve soil health.

Maintaining SOC storage at an equilibrium or increasing SOC content towards the optimal level for the local environment can contribute to achieving the SDGs (Figure 2). This can be achieved by unlocking the full ecosystem services potential of soils to enable not only the support, maintenance or improvement of soil fertility and productivity (necessary to achieve SDG 2 "Zero Hunger" and SDG 3 "Good Health and Well Being"), but also to store and supply more clean water (SDG 3 and SDG 6 "Clean Water and Sanitation"), maintain biodiversity (SDG 15 "Life on Land"), and increase ecosystem resilience in a changing climate (SDG 13 "Climate Action"). In the following sections, the focus is on food production which contributes to achieving SDG 2, biodiversity which forms part of SDG 15, and climate change mitigation as part of SDG 13.

Figure 2 · Contribution of SOC to the sustainable development goals.

2.2 · SOC AND BIODIVERSITY

Soil biodiversity reflects the mix of living organisms in the soil. These organisms interact with one another, as well as with plants and small animals, forming a web of biological activity (Orgiazzi *et al.*, 2016). On the one hand, soil biodiversity contributes greatly to the formation of SOM from organic litter, thereby contributing to the enhancement of SOC content. On the other hand, the amount and quality of SOM (and consequently SOC) determines the number and activity of soil biota that interact with plant roots. Therefore, the soil microbial community structure is influenced largely by the quality and quantity of SOC and to a lesser extent by plant diversity (Thiele-Brunh *et al.*, 2012).

2.2.1 · IMPORTANCE OF SOIL BIODIVERSITY

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

> ***"Soils are a key reservoir of global biodiversity, which ranges from micro-organisms to flora and fauna. This biodiversity has a fundamental role in supporting soil functions and therefore ecosystem goods and services associated with soils. Therefore it is necessary to maintain soil biodiversity to safeguard these functions"***
> (FAO, 2015a, p.2-3).

Soil organisms are generally classified according to their size as indicated in Table 1.

Table 1 · Overview of the main soil organisms according to their size.

ADAPTED FROM ORGIAZZI *ET AL.*, 2016; GARDI AND JEFFERY, 2009.

Size	**Microfauna** *(Size range: 1-100 mm)*	**Mesofauna** *(Size range: 100 mm-2 mm)*	**Megafauna** *(Size range: ‹2 mm)*
+	Protozoa	Collembola	Earthworms
	Nematodes	Mites	Ants
	Fungi	Tardigrades	Woodlice
-	Bacteria		Termites

Soil biodiversity (including organisms such as bacteria, fungi, protozoa, insects, worms, other invertebrates and mammals) combined with SOC shape the metabolic capacity of soils and is believed to play a crucial role in increasing food production and soil resilience to climate change. The complex soil organism communities i) determine the magnitude and direction of C fluxes between the atmosphere and soils (either by supporting soil carbon sequestration or by enhancing GHG emissions), ii) cycle SOC and majorly influence nutrient availability (in particular, nutrient acquisition by plants is highly effective when supported by symbiotic associations with soil microorganisms), iii) improve soil physical structure by promoting aggregation, and iv) promote biological pest control and crop pollination (FAO and ITPS, 2015).

Many scientists have reported the role of macrofauna in the accumulation of SOC. For example millipedes and earthworms breakdown and transform particulate organic matter. Soil macrofauna also have the ability to translocate SOC to greater soil depths where it is believed to have longer residence times (Rumpel and Kögel-Knabner, 2011).

2.2.2 · SOIL BIODIVERSITY LOSSES

Losses in soil biodiversity have been demonstrated to affect multiple ecosystem functions including decomposition of SOC, nutrient retention and nutrient cycling (FAO and ITPS, 2015). Poor land-management practices and environmental change are affecting belowground communities globally, and the resulting declines in soil biodiversity reduce and impair these benefits (Figure 3) (Wall *et al.*, 2015).

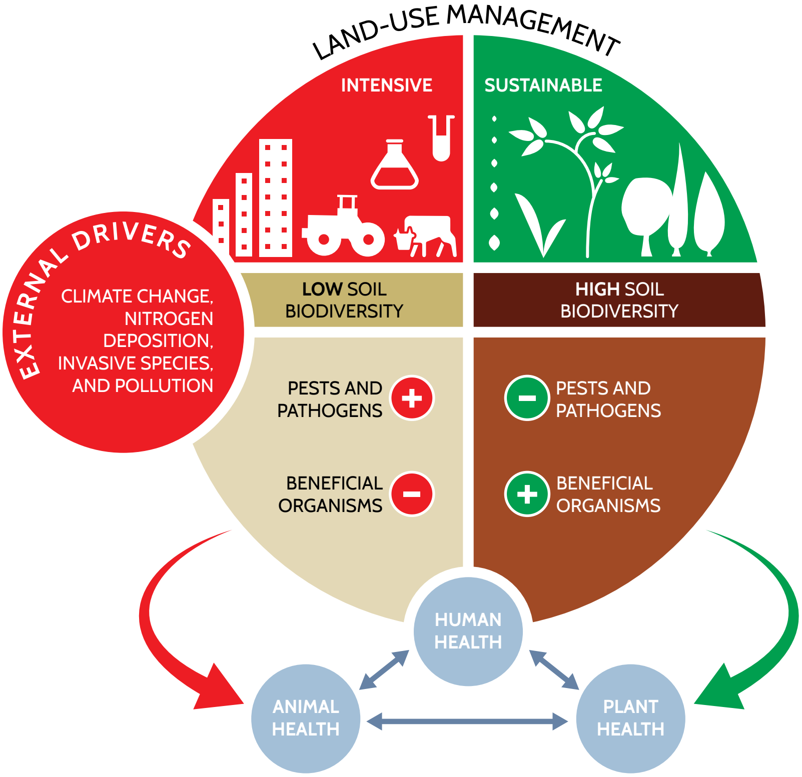

Figure 3 · Impact of land use decisions on soil biodiversity.
Modified from Wall *et al.*, 2015.

The unsustainable agricultural management practiced in many agro-ecosystems (such as monocultures, extensive use of tillage, chemical inputs) degrade the fragile web of community interactions between pests and their natural enemies, thus having negative repercussions on SOC stocks. When losses of SOC cannot be fully explained by physical soil properties, it is hypothesized that the stability of SOC is dependent on the activity and diversity of soil organisms (Gardi and Jeffery, 2009).

With ongoing losses in belowground microbial diversity, understanding relationships between soil biodiversity and C cycling is critical for projecting how the loss of diversity under continued environmental alteration by humans will impact global C cycling processes (De Graaf *et al.*, 2015).

Current research indicates that soil biodiversity can be maintained and partially restored if managed sustainably. Promoting the ecological complexity and robustness of soil biodiversity through improved management practices represents an underutilized resource with the ability to ultimately improve human health (Figure 3) (Wall *et al.*, 2015). For sustainable soil management techniques aimed at climate change mitigation and adaptation and sustainable food production, see section 5.

2.3 · SOC, FOOD PRODUCTION AND WATER SUPPLY

2.3.1 · SOIL FERTILITY FOR FOOD PRODUCTION

Soil fertility refers to the ability of soil to support and sustain plant growth, including through making nitrogen, phosphorous, sulphur, and other nutrients available for plant uptake. This process is facilitated by: i) nutrient storage in SOM; ii) nutrient recycling from organic to plant-available mineral forms; and iii) physical and chemical processes that control nutrient sorption, availability, displacement and eventual losses to the atmosphere and water. Managed soils represent a highly dynamic system, and it is this very dynamism that makes soils function and supply ecosystem services. Overall, the fertility and functioning of soils depend on interactions between the soil mineral matrix, plants and microbes. These are responsible for both building and decomposing SOM and therefore for the preservation and availability of nutrients in soils. To sustain soil functions, the balanced cycling of nutrients in soils must be maintained (FAO and ITPS, 2015).

2.3.2 · INFLUENCE OF SOC ON WATER-HOLDING CAPACITY AND POROSITY

Organic matter improves soil aggregate and structural stability which, together with porosity, are important for soil aeration and the infiltration of water into soil. While plant growth and surface mulches can help protect the soil surface, a stable, well-aggregated soil structure that resists surface sealing and continues to infiltrate water during intense rainfall events will decrease the potential for downstream flooding. Porosity determines the capacity of the soil to retain water and controls transmission of water through the soil. In addition to total porosity, the continuity and structure of the pore network are important to these functions and also to the further function of filtering out contaminants in flow (FAO and ITPS, 2015). The other soil functions related with water and their consequences in terms of enhanced water quality of food production are listed in Table 2. Finally, the water stored in soil serves as the source for 90 percent of the world's agricultural production and represents about 65 percent of global fresh water (Amundson *et al.*, 2015).

Table 2 · Soil functions related to the water cycle and ecosystem services.
From FAO and ITPS, 2015

Soil Function	Mechanism	Consequence	Ecosystem service
Stores (Storage)	Water held in soil pores supports plant and microbial communities	Biomass production Surface protection	Food Aesthetics Erosion control
Accepts (Sorptivity)	Incident water infiltrates into soil with excess lost as runoff	Storm runoff reduction	Erosion control Flood protection
Transmits (Hydraulic conductivity)	Water entering the soil is redistributed and excess is transmitted as deep percolation	Percolation to groundwater	Groundwater recharge Stream flow maintenance
Cleans (Filtering)	Water passing through the soil matrix interacts with soil particles and biota	Contaminants removed by biological degradation/ retention on sorption sites	Water quality

2.4 · CLIMATE CHANGE EFFECTS ON SOC

Current projections suggest soil carbon responses under climate change will range from small losses to moderate gains. Predicting the composite effects of climate change on soils is extremely difficult given the complex interactions between temperature and moisture, increased productivity and increased decomposition, and variations according to the regions and the soil types (FAO and ITPS, 2015; Keestrea *et al.*, 2016).

2.4.1 · EFFECTS OF RISING TEMPERATURES AND INCREASED PRECIPITATION ON SOC STOCKS

Temperature and precipitation are the most significant factors controlling SOC dynamics (Deb *et al.*, 2015). Although increasing temperatures may increase plant production, thereby increasing carbon inputs to the soil, it will also tend to increase microbial decomposition of SOC (Keestrea *et al.*, 2016). In fact, there is strong empirical support for the idea that rising temperatures will stimulate the net loss of soil carbon to the atmosphere, driving a positive land carbon–climate feedback that could accelerate climate change (Figure 4) (Crowther *et al.*, 2016). Furthermore, with climate change, more frequent extreme precipitation and drought events are projected which may have greater impacts on ecosystem dynamics than the singular or combined effects of rising CO_2 and temperature (IPCC, 2014). This increase in frequency of extreme events may exacerbate the rate and susceptibility to accelerated erosion, salinization and other degradation processes, leading to further carbon losses. Finally, climate change can impact several soil forming factors, including rainfall, temperature, micro-organisms/ biota and vegetation, thus negatively affecting the rate of SOC accumulation (FAO and ITPS, 2015).

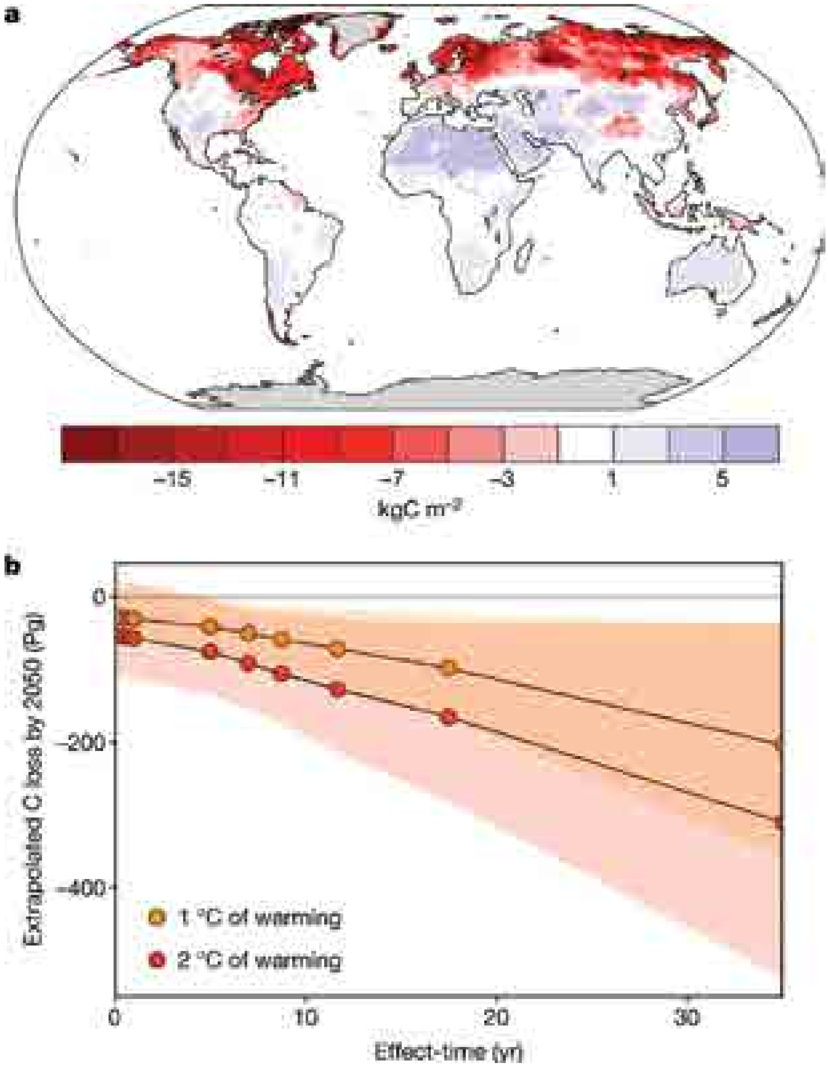

Figure 4 · Spatial extrapolation of the temperature vulnerability of SOC stocks.

From Crowther *et al.*, 2016.

a. Map of predicted changes in soil C stocks (0-15cm depth) per pixel by 2050 under the 'no acclimatization' scenario, under a 1 °C rise in global average soil surface temperature.

b. Total reductions in the global C pool under 1 °C and 2 °C global average soil surface warming by 2050, as expected under a full range of different soil C effect-time scenarios (x axis). Effect-time refers to the rate at which the full soil C response to warming is realized. Shaded areas indicate the 95 percent confidence intervals around the average C losses (dots) for each scenario.

2.4.2 · EFFECTS OF INCREASED CO_2 CONCENTRATION IN THE ATMOSPHERE

Anthropogenic increases in atmospheric CO_2 may drive increased net primary productivity (NPP), which provides the primary input of carbon to soil, as long as nutrient and water limitations do not occur. Such increased NPP is expected to stimulate plant growth, but may ultimately have a negative feedback on atmospheric CO_2 through increased inputs of SOC (Van Groenigen *et al.*, 2014; Amundson *et al.*, 2015). Indeed, the theory of progressive nutrient limitation enunciates that NPP responses to elevated CO_2 will be limited by the supply of soil nutrients, particularly nitrogen. It remains unclear whether increases in NPP will translate into increased SOC storage. Free-air CO_2 enrichment studies often observe no change in SOC despite increased NPP, possibly due to increased loss rates of C inputs or increased decomposition of SOC through the priming effect (See section 2.3.3). Finally, SOC accumulation under elevated CO_2 levels may be difficult to measure due to spatial heterogeneity in SOC pools and the short timescale of the experiments relative to SOC turnover times (Todd-Brown *et al.*, 2014).

2.4.3 · UNCERTAINTIES ABOUT THE RESPONSE OF SOC TO CLIMATE CHANGE

Numerous uncertainties remain when trying to make projections on SOC behaviour as a function of climate change. Indeed, the consequences of human actions on the global climate are still uncertain, partly owing to a limited understanding about soil respiration and its representation in Earth system models (Gougoulias *et al.*, 2014). For example, a high uncertainty concerns the so-called “priming effect” on SOM decomposition which is one of the crucial processes in ecosystem carbon balances. The priming effect is defined as the increase in decomposition of SOC stocks as a result of addition of easily degradable compounds (Van der Wal and de Boer, 2017). This effect adds uncertainty to the prediction of future soil C responses to a changing climate because its mechanisms are still not fully understood or known (FAO and ITPS, 2015). As underlined by Gougoulias *et al.* (2014), microbial contributions to climate change through carbon cycle feedbacks are far from straightforward, but add further uncertainty because of simultaneous direct and indirect effects and interactions with other factors. Regarding soil microbes, many questions remain unanswered about the time needed for the effects of warming to be consummated and how long soil communities take to adapt to warmer environments (Crowther *et al.*, 2016).

BOX 1 · SENSITIVITY OF SOC HOT-SPOTS AND BRIGHT SPOTS TO CLIMATE CHANGE

The effects of climate warming are contingent on the size of the SOC stock, with considerable losses occurring in high-latitude areas. Thus, hot-spots of SOC reaction to climate change are of high concern (FAO and ITPS, 2015). Permafrost areas, which have been demonstrated to have the largest standing SOC stocks and the fastest expected rates of warming, are crucially endangered by warming (Crowther *et al.*, 2016). When thawing occurs in reaction to warming, SOC reserves of permafrost soils that were previously frozen and thus protected from decomposition for millennia, are remobilized and become available for biological decomposition (FAO and ITPS, 2015). Large pools of SOM that were previously protected from decomposition may become available for biological decomposition (mineralization), leading to increased GHG fluxes to the atmosphere (Figure 5) (Tarnocai *et al.*, 2009; Hugelius *et al.*, 2013; Hugelius *et al.*, 2014; FAO and ITPS, 2015; Batjes, 2016). Similarly, peatlands may also be highly sensitive to climate change due to their expected higher evapotranspiration rates as a result of increasing temperatures. Indeed, when these soils heat up, or if they become drier, vast quantities of carbon are likely to be lost (Keestrea *et al.*, 2016).

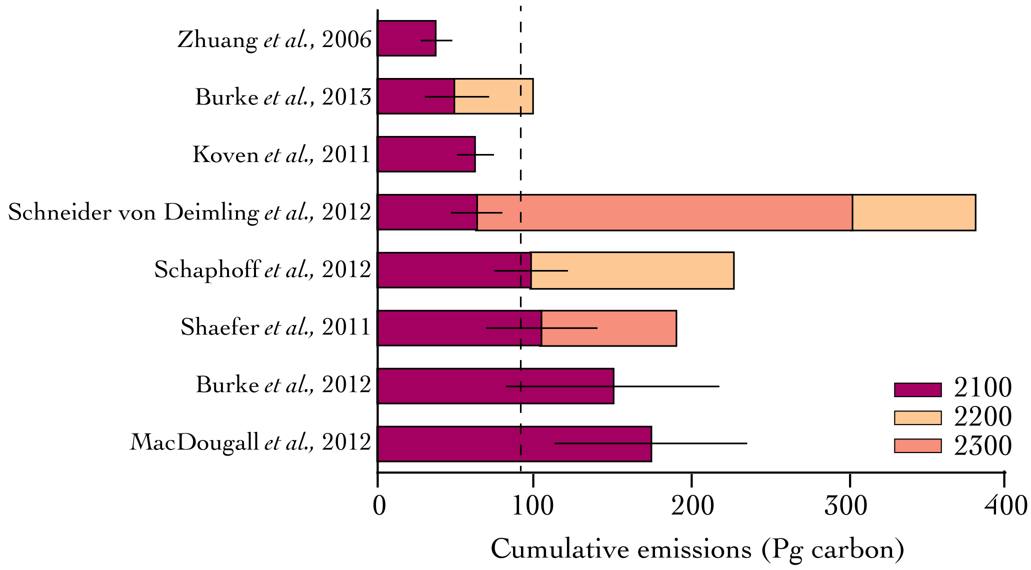

Figure 5 · Model estimates of potential cumulative carbon release from thawing permafrost by 2100, 2200 and 2300.

From Schuur *et al.*, 2015.

All estimates except those of Schaphoff *et al.* (2013) and Schaefer *et al.* (2011) are based on the most pessimistic IPCC scenarios in terms of Climate Change Mitigation (RCP 8.5 in the Fifth Assessment Report (AR5, 2013) and A2 in the AR4 (2007)). Error bars show uncertainties for each estimate that are based on an ensemble of simulations assuming different warming rates for each scenario and different amounts of initial frozen C in permafrost. The vertical dash line shows the mean of all models under the current warming trajectory by 2100 (Schuur *et al.*, 2015)

Due to climate change, drylands are expected to expand and their SOC stocks are likely to be reduced (Figure 6). This would be caused by higher temperatures leading to a higher vapour pressure deficit and evaporative demand, and decreased soil moisture which may lead to an even stronger impact of temperature extremes. The average temperature increase is expected to be most significant in drylands, approximately about 1.8 times greater than the increase in humid regions. Furthermore, SOC storage decreases with increasing temperature and increases with increasing soil water content (described in section 2.3). Finally, erosion-induced land degradation may also lead to the emission of carbon (Huang *et al.*, 2015).

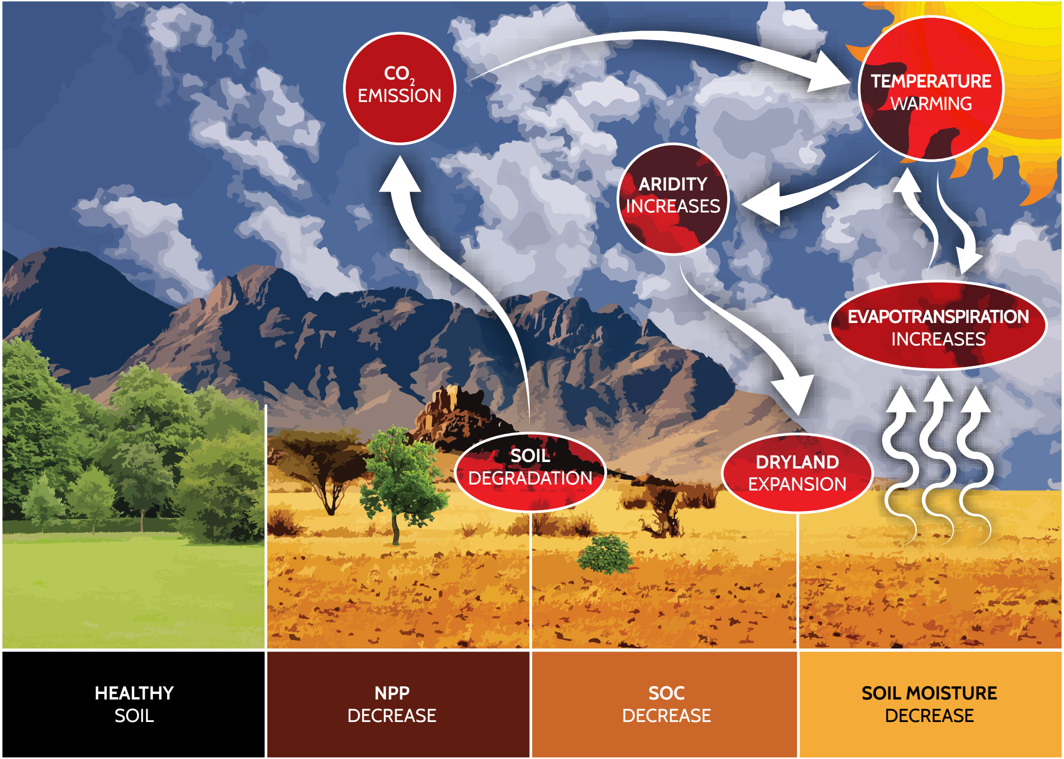

Figure 6 · Schematic diagram of positive feedback cycles and dryland expansion due to climate change and SOC decrease.

Modified from Huang *et al.* 2015

2.5 · IMPORTANCE OF SOC IN THE INTERNATIONAL FRAMEWORK OF CLIMATE CHANGE MITIGATION AND ADAPTATION

Climate change has been at the center of various international agreements since the 1980s (Box 2). Soils are considered in many of these agreements as the biggest carbon reservoirs on Earth (See section 1.1). Therefore, in future, GHG emissions from soils need to be further studied to enable better reporting of national GHG inventories to the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement.

It is thus crucial to have a good knowledge of the current global SOC stock and its spatial distribution to inform various stakeholders (e.g. farmers, policy makers, land users) to make the best use of available land and provide the best opportunities to mitigate and adapt to climate change, but also ensure sufficient food production and water supply.


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BOX 2 · KEY AGREEMENTS AND DECISIONS ON CLIMATE CHANGE WITH CONSIDERATION OF SOILS

- **1988: Creation of the International Panel on Climate Change (IPCC)** by the World Meteorological Organization (WMO) and the United Nations Environment Programme.
- **1992: Rio Conference on Environment and Development and adoption of the three UN Conventions (UNCCD, UNFCCC, UNCBD)**

ARTICLE 4 OF THE UNFCCC:

All Parties shall develop, periodically update, publish and make available to the Conference of the Parties (COP) national inventories of anthropogenic emissions by sources and removals by sinks† (…) [including CO_2, CH_4 and N_2O] and; Formulate, implement, publish and regularly update (…) measures to mitigate climate change (…) and measures to facilitate adequate adaptation to climate change.

- **1997: Adoption of the Kyoto Protocol (KP)**

ARTICLE 3 OF THE KP ACCOUNTS FOR MITIGATION:

The net changes in GHG emissions by sources and removals by sinks† resulting from direct human-induced land-use change and forestry activities since 1990, measured as verifiable changes in carbon stocks.

- **2015: Signature of the Paris Agreement**
- **2016: Entry into force of the Paris Agreement**

ARTICLE 4:

In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of GHG emissions as soon as possible, and to undertake rapid reductions so as to achieve a balance between anthropogenic emissions by sources and removals by sinks† of GHG in the second half of this century;

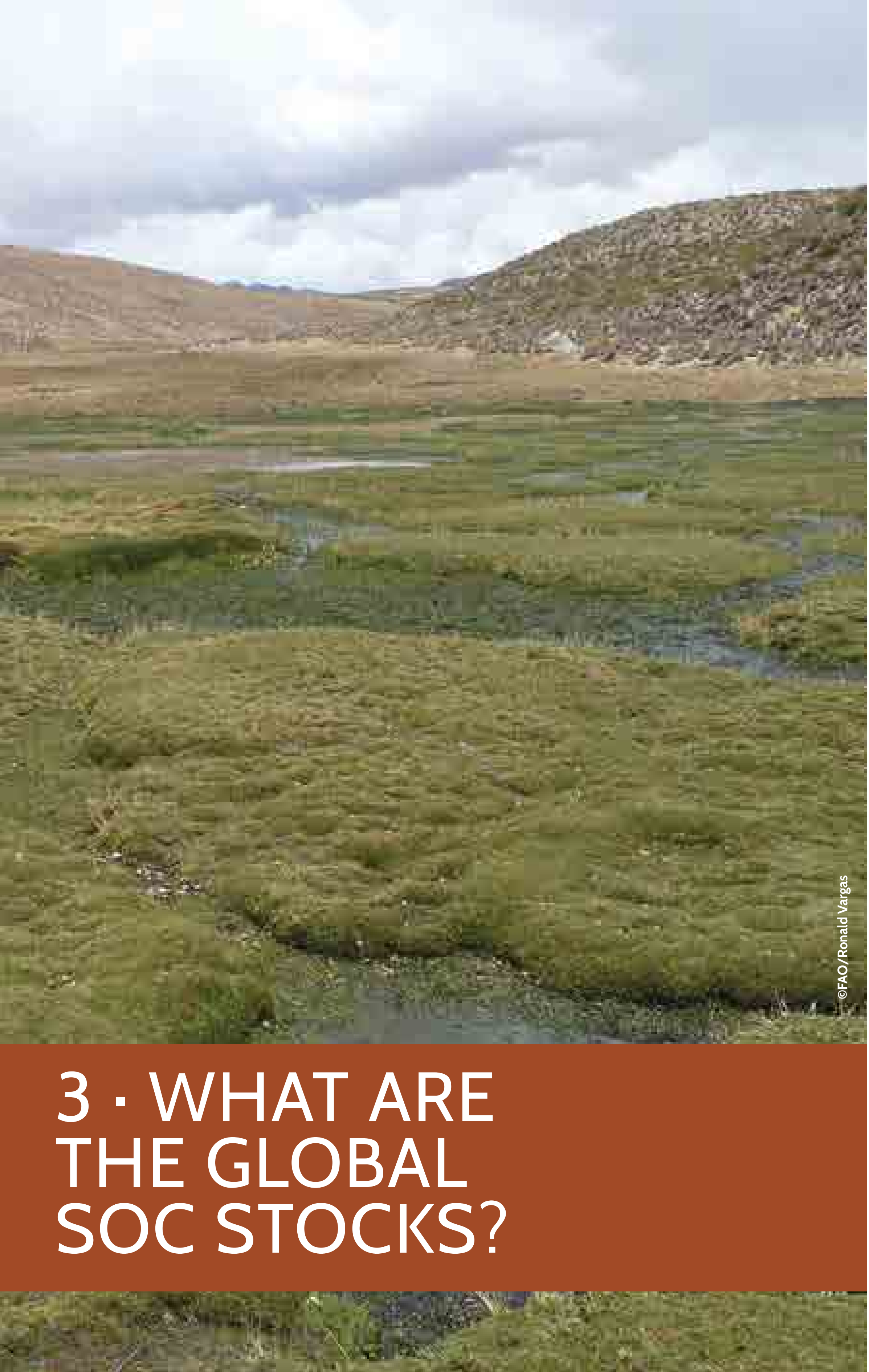
Each Party shall prepare, communicate and maintain successive nationally determined contributions (NDCs) that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions.

ARTICLE 13:

Each Party shall regularly provide a national inventory report of anthropogenic emissions by sources and removals by sinks† of GHG.

- ***March 2017: 192 Parties have ratified the Kyoto Protocol, 197 Parties to the UNFCCC, and 133 Parties have ratified the Paris Agreement.***

†Soils are targeted as the major carbon reservoir on Earth.



3 · WHAT ARE THE GLOBAL SOC STOCKS?

3.1 · CURRENT GLOBAL SOC STOCKS

The magnitude of the SOC storage is spatially and temporally variable and determined by different abiotic and biotic factors (Weissert *et al.*, 2016). Globally, the largest SOC stocks are located in hot-spots such as wetlands and peatlands, most of which occur in regions of permafrost and in the tropics (Gougoulias *et al.*, 2014; Köchy *et al.*, 2015). Other cases of high SOC content occur as soil horizons buried (>1 m) by volcanic, aeolian, alluvial, colluvial, glacial and anthropogenic processes (O'Rourke *et al.*, 2015) (Figure 7).

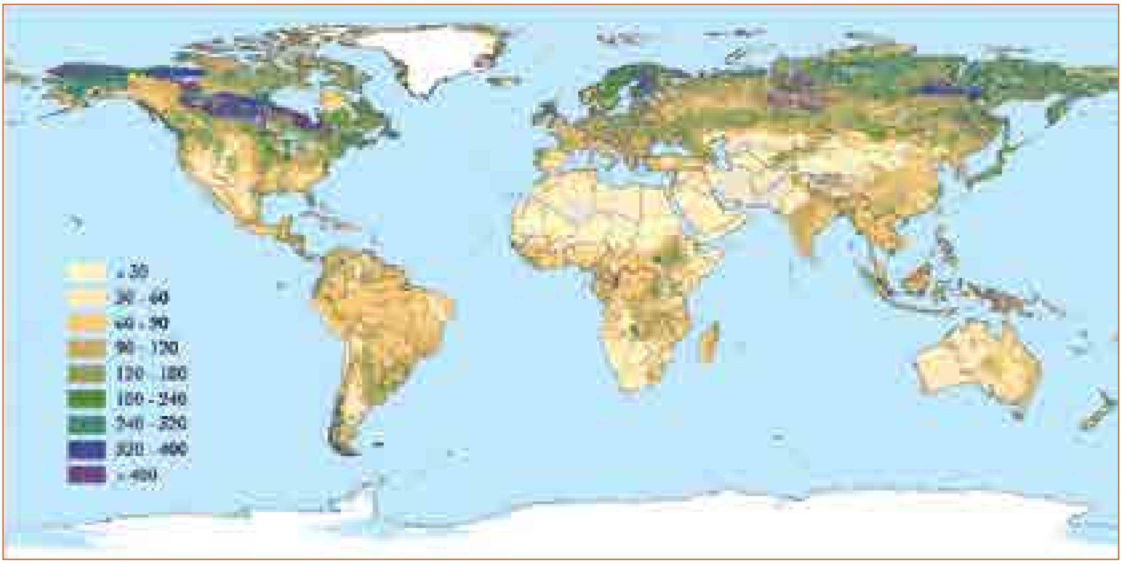


Figure 7 · Most recent map of SOC content to 1 m depth (MgC ha^{-1}).
From Batjes, 2016.
Note that 1 Mg= 1t=10-9 Pg.
Information on the calculation method is indicated on Table 2 on next page.

Although global SOC stocks have been estimated to be about 1 500 PgC for the topmost 1 m (FAO and ITPS, 2015), Table 3 demonstrates the high variability of SOC estimates over time and according to different calculations and methods used. Even the most recently published global SOC maps are based on historical data that has been collected over long periods of time rather than data obtained from recent and/or current monitoring.

Table 3 · Review of global SOC stocks estimates.

	SOC stock (PgC)				
Reference	**0-30cm**	**0-100cm**	**0-200cm**	**0-300cm**	Method
Batjes (1996)	684-724	1 462-1 548	2 376-2 456		Geo-referenced database (WISE[1] – 4 353 soil profiles) + DSMW[2]
Jobbágy and Jackson (2000)		1 502	1 993	2 344[3]	2 721 soil profiles grouped by biome. NSCD[4], WISE and a database from the Canadian Forest Service[5]
Global Soil Data Task Group (2000) – International Geosphere-Biosphere Programme		1 550 (SOC stock x grid cell area)			WISE data (v.1 - 1 125 profiles) + DSMW
Hiederer and Köchy (2011)		1 417			HWSD[6] version 1.1
Scharlemann *et al.* (2014)		1 461 (504-3 000)			Review of publications from 1951 to 2011
Shangguan *et al.* (2014)		1 455	230 cm: 1 923		DSMW and regional/national soil databases
Köchy *et al.* (2015)		1 062			HWSD + adjusted bulk density for organic soils
		1 325			HWSD + adjusted bulk density for organic soils + improved for peatland
Batjes (2016)	755	1 408	2 060		WISE30sec database + HWSD v1.2 adapted

1 World Inventory of Soil Emission Potentials;

2 Digital Soil Map of the World, 1961-1981 by IUSS, FAO and UNESCO;

3 According to Tarnocai *et al.* (2009) that value may underestimate the total mass of organic material stored in regions of permafrost

4 National Soil Characterization Database, produced and updated by the US Department of agriculture (1994) characterizes 5307 profiles around the world;

5 Emphasises Canadian Forest and Tundra soils (1997);

6 Harmonized World Soil Database, based on the DSMW with updates of soil information worldwide. Version 1.1 released in 2009 and version 1.2 in 2012.

3.2 · HOT-SPOTS AND BRIGHT SPOTS OF SOC: MAJOR AREAS FOR CONSIDERATION

The distribution of SOC is very heterogeneous and is strongly dependant on soil type, land use and climatic conditions. On certain soil types and under certain land uses, SOC storage is highly effective. Although they cover proportionally little of the global land surface, these areas require special attention: they are hot-spots of SOC. These hot-spots are very sensitive to climate change and can easily become sources of GHG emissions due to their high SOC content (Box 1). Finally, large land areas with low SOC stocks per km^2 represent a potential for further carbon sequestration: they are bright spots of SOC.

3.2.1 · BLACK SOILS

Black soils, broadly defined here as soils that contain a mollic horizon, cover about 7 percent of the ice-free land surface (916 million ha). Most of them occur in three regions in the northern hemisphere and one region south of the equator. The natural areas from which black soils developed are the prairies and steppes that experience summer-dry and freezing conditions (Altermann *et al.*, 2005; Liu *et al.*, 2012). These soils are dark brown to black in colour due to their enrichment of high-quality humus down to a depth of more than 40 cm - mostly 60 to 80 cm. This high-quality humus is the result of a high base saturation (i.e. a high percentage of the cation exchange capacity is occupied by the basic cations Ca^{2+}, Mg^{2+} and K^{+}), stabile aggregate structure, and intensive biological mixing (bioturbation, e.g. by earthworms) (Altermann *et al.*, 2005). In the World Reference Base (WRB) for soil resources, black soils include Chernozems, Kastanozems and Phaeozems. For Chernozems, the SOC content ranges between 2.9 and 3.5 percent in the upper 10 cm, and exceeds 1.2 percent at the lower boundary of the chernic horizon (FAO and ITPS, 2015). Due to their high productivity, most of these soils are intensively used for agriculture. However, they are very sensitive to soil degradation (e.g. erosion, crusting and nutrient mining) and SOC losses and need to be managed carefully to maintain their productive potential (Liu *et al.*, 2012).

3.2.2 · PERMAFROST

Low temperatures and waterlogging in permafrost terrain reduces decomposition rates and increases cryoturbation as a result of freeze-thaw processes. In addition, depositional environments dating back to the Pleistocene era has led to the accumulation of large stocks of SOC in the active layer and underlying permafrost (Hugelius *et al.*, 2013; Ping *et al.*, 2015). SOC accumulation in these soils make them important for the global climate system because of their potential to thaw, and thus decompose organic matter accumulated over a long period (Box 1) (Ping *et al.*, 2015). Although the repartition of permafrost is globally known, SOC estimates in the permafrost region remain variable (Table 4). However, it is considered that about 30 percent of the total SOC stock to 2 m depth is held in the Northern Circumpolar Region and that the permafrost region contains twice as much carbon as there is currently in the atmosphere (Schuur *et al.*, 2015).

Table 4 · Recent estimates of SOC stocks in the permafrost region.

	SOC stocks (PgC)			
Reference	**0-30cm**	**0-100cm**	**0-300cm**	**Method**
Tarnocai *et al.* Pan	191	496	1 024	Northern Circumpolar Permafrost region using the NCSCDB[1]
Hugelius *et al.*, 2014	217 ± 12	472 ± 27	1 035 ± 150	Same methodology as Tarnocai *et al.* (2009) but using revised and gap filled data from Hugelius *et al.* (2013)

[1] Northern Circumpolar Soil Carbon database – Includes soil profile data not included in the HWSD.

3.2.3 · PEATLANDS

Peatlands are wetland ecosystems characterized by the accumulation of organic matter (peat) derived from dead and decaying plant material under conditions of permanent water saturation (Parish *et al.*, 2008; Orgiazzi *et al.*, 2016). Peatlands and organic soils contain 30 percent of the world's soil carbon but only cover 3 percent of the Earth's land area (3.8 Mm^2 based on the Global Peatland Database – GPD) occurring across 180 countries. Most of them occur in regions of permafrost and in the tropics. There, high plant productivity combines with slow decomposition as a result of high rainfall and humidity (Figure 8) (Parish *et al.*, 2008; FAO, 2012; Klingenfuß *et al.*, 2014). Peatlands, which have a depth equal to or above 30 cm, contain a total SOC mass of 447 PgC for their total depth, according to the GPD, although uncertainties around this estimate remain high (Köchy *et al.*, 2015). Specifically, uncertainty in peat depth remains the largest obstacle to estimating the size of regional and global peatland C pools. The global estimated mean peat depth of 2.3 m is admittedly uncertain, and within many regions information on peat depth is lacking, contributing to uncertainty in peatland C storage (Buffam *et al.*, 2010).

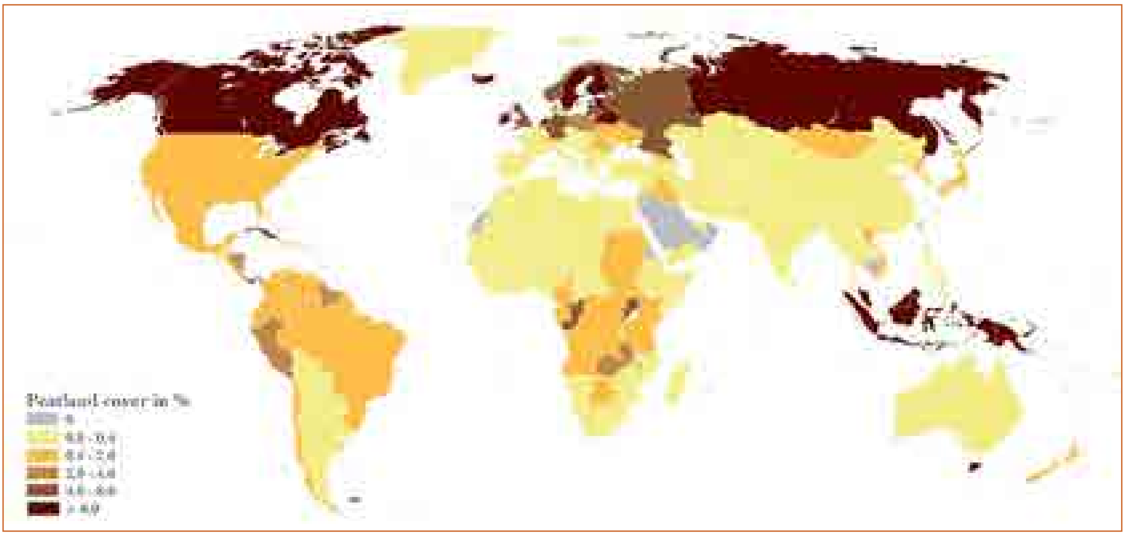


Figure 8 · Peatland distribution in the world.
From Parish *et al.*, 2008

3.2.4 · GRASSLANDS

Grasslands, which include rangelands, shrublands, pasturelands, and croplands sown with pasture and fodder crops, covered approximately 3.5 billion ha in 2000 (Figure 9). Grasslands cover approximately 40 percent of the earth's land surface (McSherry and Ritchie, 2013; Orgiazzi *et al.*, 2016), represent 70 percent of the global agricultural area, and contain about 20 percent of the world's SOC stocks (FAO and ITPS, 2015). Around 20 percent of the world's native grasslands have been converted to cultivated crops, and significant portions of world milk (27 percent) and beef (23 percent) production occur on grasslands managed solely for those purposes. The livestock industry – largely based on grasslands – provides livelihoods for about 1 billion of the world's poorest people and one third of global protein intake. One of the reasons for the intensive use of grasslands is their high natural soil fertility. Grasslands characteristically have high inherent SOM content, averaging 333 Mg ha^{-1}. However, the Land Degradation Assessment in Drylands (LADA) estimated that about 16 percent of rangelands are currently being degraded (Conant, 2010).

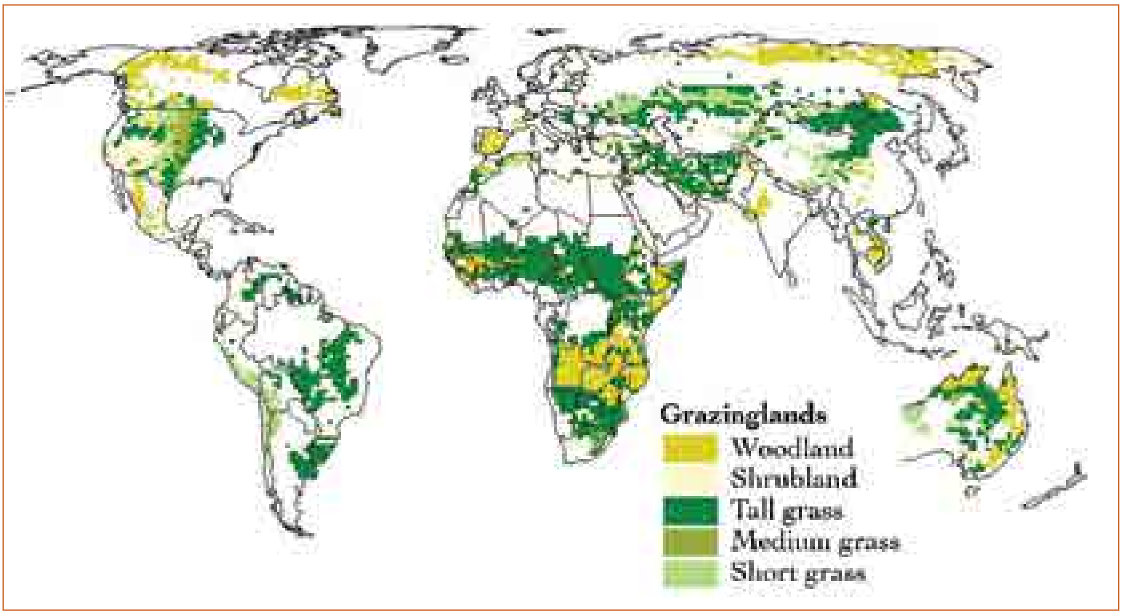


Figure 9 · Grassland distribution in the world.
From Conant, 2010

3.2.5 · FOREST SOILS

Forests cover 4.03 billion ha globally, approximately 30 percent of Earth's total land area. The majority of soil carbon is concentrated in peatlands within the boreal forests and the tropical forests in Southeast Asia (Figure 10) (Pan *et al.*, 2013). Forest vegetation and soils contain about 1 240 PgC, and the carbon stock varies widely among latitudes. Of the total terrestrial C stock in forest biomes, 37 percent is in low latitude forests, 14 percent in mid latitudes and 49 percent in high latitudes. The SOC stock may comprise as much as 85 percent of the terrestrial C stock in the boreal forest, 60 percent in temperate forests and 50 percent in tropical rainforest. A large part of the total SOC stock occurs in soils of tundra, pre-tundra and taiga regions. The SOC content in forest soils may range from 0 percent in very young soils to as much as 50 percent in some organic or wetland soils, with most soils containing between 0.3 and 11.5 percent in the surface 20 cm of mineral soil (Lal, 2005). Around the world, deforestation causes about 25 percent of the total loss of SOC (FAO and ITPS, 2015).

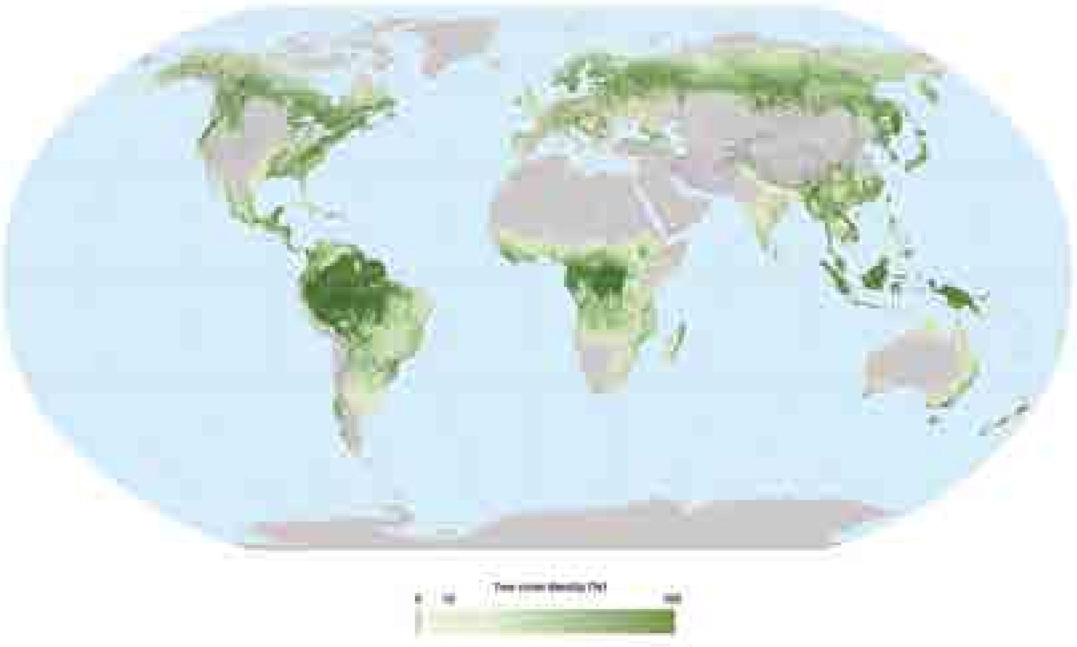


Figure 10 · Forest distribution in the world.
From FAO, 2010

3.2.6 · DRYLANDS

Drylands cover approximately 430 million ha, which comprise 40 percent of the Earth's surface (Figure 11) (FAO and ITPS, 2015). Although there is no clear boundary, drylands are considered to be areas where average rainfall is less than the potential moisture losses through evaporation and transpiration (FAO, 2004). The soils of drylands are characterized by frequent water stress, low organic matter content and low nutrient content. However, their carbon storage accounts for more than one third of the global stock, mainly due to their large surface area and long-term SOC storage (when the soil is not degraded), rather than due to vegetation cover. Drylands have the potential to sequester more carbon than as they are far from saturated (United Nations, 2011), but carbon storage in drylands is affected and limited by various bioclimatic elements and is slow. Furthermore, these lands are susceptible to various types of degradation, including wind erosion, and certain management practices therefore easily result in degradation. Therefore, dryland soils need to be sustainably managed to maintain their existing SOC levels and foster their SOC sequestration potential (United Nations, 2011; FAO and ITPS, 2015).

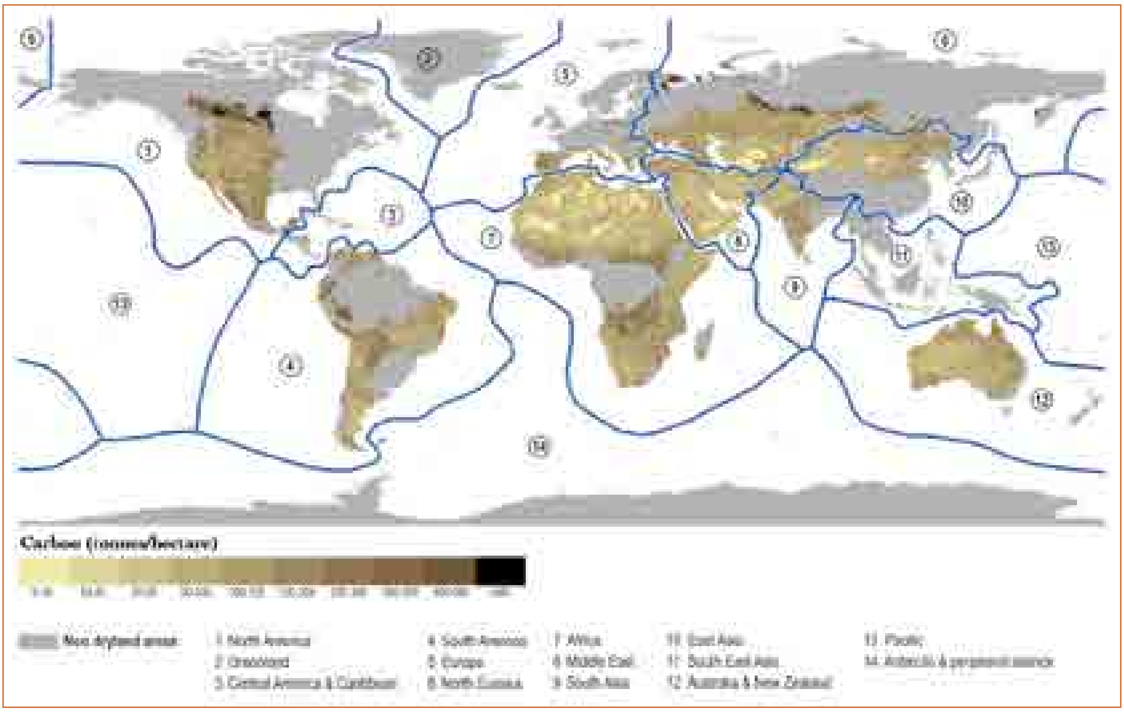


Figure 11 · Carbon mass per hectare throughout the drylands.
From United Nations, 2011

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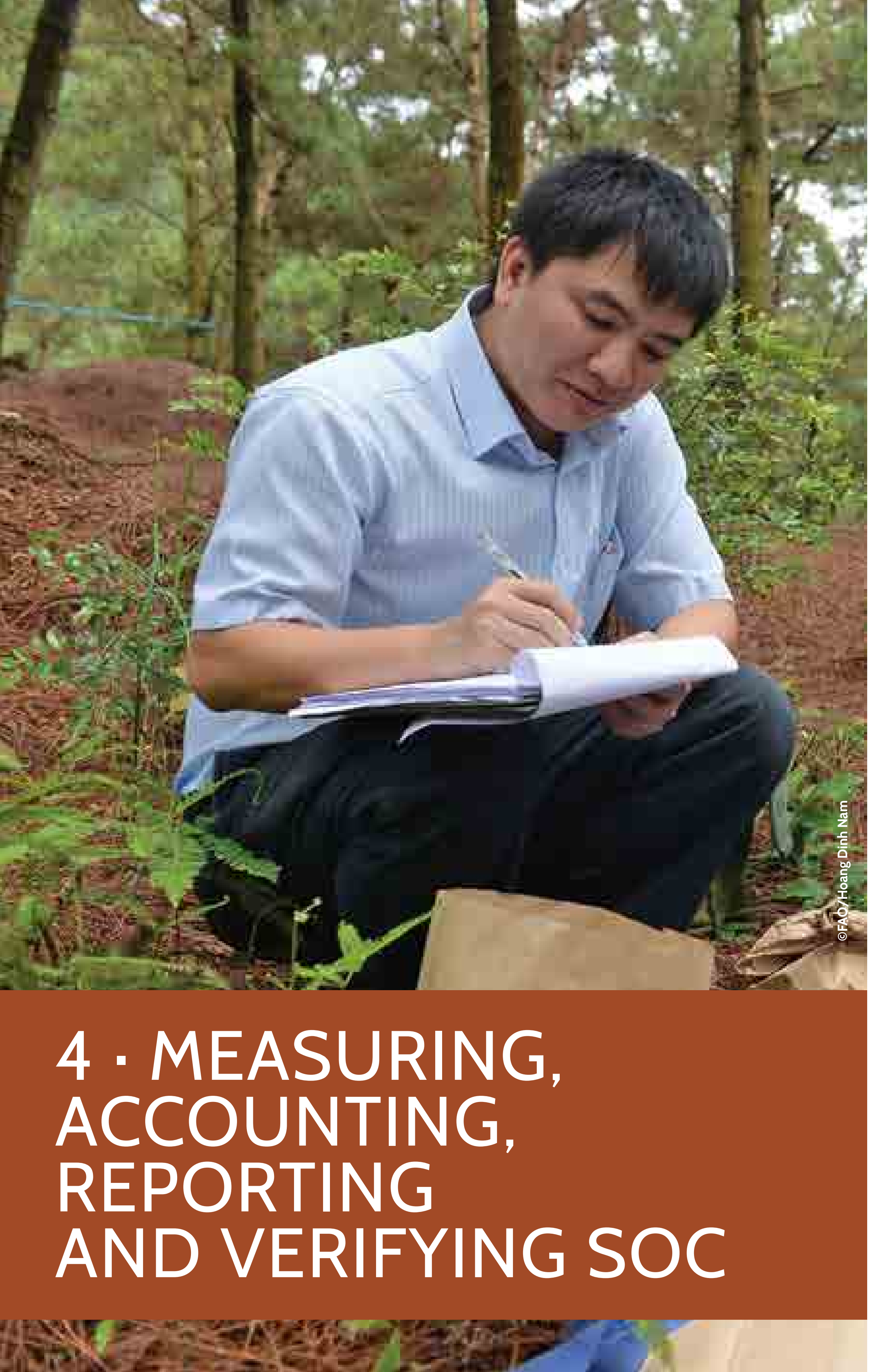

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4 · MEASURING, ACCOUNTING, REPORTING AND VERIFYING SOC

4.1 · MEASURING, REPORTING AND VERIFYING (MRV)

4.1.1 · WHAT IS MRV AND WHAT IS IT USED FOR?

Under the UNFCCC, countries are required to have a national system of institutional and legal arrangements in place to ensure the proper and timely management of and reporting on GHG emissions to the atmosphere (e.g. through mineralization of SOM) and removals from the atmosphere (e.g. SOC sequestration). Such reporting systems are referred to as measuring, reporting and verification (MRV) systems in which:

- Measurement (M) refers to the annual amount of SOC stock changes determined by human activities, including mitigation actions, and associated anthropogenic GHG emissions and removal (UNFCCC, 2014).
- Reporting (R) refers to the analysis and compilation of data measured through various reports, e.g. National Communications, National GHG Inventories, and Biennial Update Reports in which countries give an account of the results of their actions to address climate change (UNFCCC, 2014).
- Verification (V) refers to the process of independently checking transparency, completeness, accuracy and consistency of reported information and of methods used to generate that information. By providing feedback on quality of information and methods, together with suggestions for their improvement, verification also provides quality assurance and quality control (QA/QC) that improves the entire MRV process (FAO, 2015).

Overall, MRV aims to ensure that the data collected in national GHG national inventories (and consequently in SOC stock inventories) are (IPCC, 2006):

- **Transparent**: documentation is sufficient and clear enough to allow any stakeholder other than the inventory compilers to understand how the inventory was compiled and the good practice requirements (see section 4.1.2) are met.
- **Complete**: estimates are reported for all relevant categories of sources and sinks (e.g. soil carbon pool), and gases. When elements are missing, their absence should be clearly documented together with a justification for exclusion.
- **Consistent**: estimates are made in such a way that differences in the results between years and categories reflect real differences in emissions. Annual inventory trends should be calculated using the same method and data sources in all years and should aim to reflect the real annual fluctuations in emissions or removals and not be subject to changes resulting from methodological differences.
- **Comparable**: the inventory is reported in a way that allows it to be compared with inventories for other countries.
- **Accurate**: the inventory contains neither over- nor under-estimates so far as can be ascertained.

Under the Paris Agreement (United Nations, 2015), all ratifying countries have committed to make nationally determined contributions (NDC) to mitigate climate change, to report on their anthropogenic emissions and removals, and to track progress of their contributions to climate change mitigation. The MRV framework tracks and assesses the implementation of mitigation contributions, as well as of the policies and measures articulated under countries' NDCs (WRI, 2016). Article 13 of the Paris Agreement introduced a new Enhanced Transparency Framework for reporting, allowing for better transparency in reporting on GHG emissions.

4.1.2 · GUIDANCE FOR REPORTING ON SOC IN THE GHG INVENTORIES

Each country has to report regularly to the UNFCCC/Paris Agreement on its level of GHG emissions (e.g. CO_2, CH_4 and N_2O). Even if the form of these regular reports is likely to vary according to the country's status (Annex 1, Non-Annex 1 or Least Developed Country (LDCs)), each country is required to provide quality information on its level of GHG emissions and evolutions in order to demonstrate its willingness and efforts to meet the international requirements to limit global warming (UNFCCC, 2016).

To estimate SOC changes and associated anthropogenic GHG emissions and removals from the SOM pool, countries have to follow the methodology provided by the IPCC in its Guidelines for National GHG Inventories. Default methodologies and default factors for reporting on SOM stocks are given in volume 4 ("Agriculture, Forestry and Other Land Use" - AFOLU) of the 2006 IPCC Guidelines for National GHG Inventories and its Wetlands Supplement (which focuses on inland organic soils, coastland soils and inland wetlands mineral soils). The other five C pools for which GHG estimates have to be reported are the above-ground biomass, below-ground biomass, dead wood and litter and the harvested wood products (IPCC, 2006).

4.1.2.1 · USE OF A LAND USE AND LAND USE CHANGE (LU/LUC) MATRIX

The IPCC guidelines stratify the reporting on SOM (and consequently on SOC) in six different land use (LU) categories and thirty land use change (LUC) categories as shown, for instance in the land use matrix in Table 5 (IPCC, 2006).

Table 5 · Example of a simplified land use conversion matrix.
Adapted from the IPCC 2006 Guidelines for GHG Inventories.
Numbers represent area units (for example Mha)

Initial LU / **Final LU**	Forest Land	Grassland	Cropland	Wetland	Settlement	Other Land	Final sum
Forest Land	15	3	1				19
Grassland	2	80					82
Cropland			29				29
Wetland				0			0
Settlement	1	1	1		5		8
Other Land						2	2
Initial sum	18	84	31	0	5	2	140

4.1.2.2 · DIFFERENT CALCULATIONS FOR DIFFERENT TYPES OF SOIL

Calculation of SOC stocks differ according to the type of soil (organic soil or mineral soil) (IPCC, 2006). Organic soils are identified on the basis of criteria 1 and 2, or 1 and 3 listed below (FAO, 1998):

1. Thickness of organic horizon greater than or equal to 10 cm. A horizon of less than 20 cm must have 12 percent or more organic carbon when mixed to a depth of 20 cm.
2. Soils that are never saturated with water for more than a few days must contain more than 20 percent organic carbon by weight (i.e., about 35 percent organic matter).
3. Soils are subject to water saturation episodes and have either:
    a. at least 12 percent organic carbon by weight (i.e., about 20 percent organic matter) if the soil has no clay; or
    b. at least 18 percent organic carbon by weight (i.e., about 30 percent organic matter) if the soil has 60 percent or more clay; or
    c. an intermediate, proportional amount of organic carbon for intermediate amounts of clay.

All other types of soils are classified as mineral. Default mineral soil classifications are based on either the United States Department of Agriculture (USDA) taxonomy or on the WRB for Soil Resources Classification (FAO, 1998). Both classifications produce the same default IPCC soil types. The default mineral soils classification should be used with IPCC default reference C stock and stock change factors (stratified according to LU/LUC).

The IPCC methodological guidelines follow two different general approaches for reporting C stock changes:

1. For organic soils, it is based on the assumption that organic soils exchange GHGs with the atmosphere when impacted by human activities (e.g. drainage or rewetting) for as long as the human activity continues, or until the soil loses enough organic matter to become a mineral soil.
2. For mineral soils, it is based on the assumption that, within a climatic zone and soil type, the SOC is at equilibrium under a constant land use, system of management practices, and regime of disturbances. Consequently, any change in land use and/or in the system of management practices and/or disturbance regime brings about a SOC change that is assumed to occur linearly across a time period, established by default over 20 years.

4.1.2.3 · DIFFERENT LEVELS OF INFORMATION: USE OF METHODOLOGICAL TIER LEVELS

The IPCC 2006 Guidelines were designed on three-tiered approaches for reporting C stock changes and GHG emissions and removals, including those from SOM. Table 6 gives an overview of the differences between the three tiers. Generally, moving from lower to higher tiers improves the inventory's accuracy and reduces uncertainties, but the complexity and resources required for conducting inventories also increase.

Table 6 · Tier levels for GHG monitoring.

Adapted from the IPCC 2006 Guidelines for GHG Inventories.

Tier 1	Tier 2	Tier 3
• Designed to be the simplest to use. • Equations and default parameter values (e.g. emission and stock change factors) are provided by the IPCC guidelines. • Often spatially coarse data.	• Can use the same methodological approach as Tier 1, but applies emission and stock change factors that are based on country- or region-specific data for the most important land use or livestock categories. • Country-defined emission factors are more appropriate for the climatic regions, land use systems and livestock categories in that country. Higher temporal and spatial resolution and more disaggregated activity data are typically used.	• Higher order methods used. • Including models and inventory measurement systems tailored to address national circumstances, repeated over time, and driven by high-resolution activity data and disaggregated at sub-national level. • Greater certainty than lower tier estimates. • May include comprehensive field sampling repeated at regular time intervals and/or GIS-based systems of age, class/production data, soils data, and land use and management activity data.

IPCC default methods limit the depth of the soil layer for which SOC changes are estimated to 30 cm, although countries may measure SOC and SOC changes for deeper layers (in such cases the IPCC default factors are not applicable).

In 2019, a refinement to the current methodological guidelines will be released with a particular focus on methods applied to soils. The refinement will address several aspects such as the need to update i) default values for SOC and SOC change factors, ii) emission and removal factors, and iii) guidance for higher Tier methods for all six land sectors, but with special focus on cropland and managed grasslands. The refined guidelines will take into account the scientific advances made in measuring and reporting SOC (i.e. remote sensing, GIS, etc.). To support this and future assessments, country-specific reference SOC stocks are needed. Guidance will also focus on land representation, especially on identifying and tracking land use and management systems and associated changes over time (IPCC, 2015).

4.2 · MEASURING AND MONITORING SOC

4.2.1 · MEASURING SOC

4.2.1.1 · SOC CONTENT MEASUREMENT METHODS

To facilitate and ensure monitoring on a regular basis, SOC stock should be measured using a method that is cost-effective and can cover a high variety of soil types. However, analysing SOC by a single method that can be applied in diverse circumstances is a great challenge since SOC is not evenly distributed over large areas, depths, soil types and landscape positions. Therefore, several methods to measure and assess SOC dynamics have been developed. To date, there is no standardized approach to measure total soil carbon concentration (Laurenz and Lal, 2016). Annex 1 provides an overview of the main measurement methods for SOC and SOM contents, showing their advantages/disadvantages and current applications. Innovative methods that can rapidly and inexpensively characterize SOC, such as visible and near-infrared (Vis-NIR) and mid-infrared (MIR) reflectance spectroscopy have produced good results for the prediction of SOC content (Viscarra Rossel *et al.*, 2006; Miltz and Don, 2012). At the same time, methods that have been developed in the past, such as wet and dry oxidation, are still commonly used, especially in developing countries. Dry combustion for SOC measurement may be recommended rather than the more commonly used and cheaper Walkley and Black method, because the latter requires correction factors for incomplete oxidation. Dry combustion has high analytical costs, however, and requires extensive sample preparation and destruction. The application of this analytical method in reference laboratories has been regarded necessary to build large spectral libraries and develop accurate calibration models (Shepherd and Walsh, 2002). However, innovative modelling approaches, such as memory-based learning combined with stratified analyses are promising means to optimize calibration and unlocking the potential of spectroscopic techniques to accurately and quickly determine SOC (Jaconi *et al.*, accepted).

4.2.1.2 · CALCULATION OF SOC STOCKS

SOC stocks are computed by multiplying the proportion of organic carbon (i.e., %C divided by 100) by the depth increment, bulk density (BD), and the proportion of coarse-fragment free soil (i.e., < 2 mm fragments) in the depth increment. The coarse fragment-free proportion is on a mass basis (i.e., mass of coarse fragment-free soil/ total mass of the soil). However, depending on the soil type, SOC stock is calculated using different parameters (Box 3). For peat soils and organic soils in general, the determination of SOC stock is rather difficult. In order to calculate C stocks for peat, it is necessary to know the extent (area) of peat (and peat types), the peat depth, %C and BD which are difficult to obtain (GSP Secretariat and ITPS, 2016).

BOX 3 · CALCULATION OF SOC STOCKS FOR DIFFERENT TYPES OF SOILS

Equation 1: Determination of SOC stock for mineral Soils

$$\mathrm{SOC}_{\mathrm{stock}} = d * \mathrm{BD} * (C_{\mathrm{tot}} - C_{\mathrm{min}}) * \mathrm{CF}_{\mathrm{st}})$$

Where:
SOC = soil organic carbon stock [$\mathrm{kg\ m^{-2}}$]
C_{tot} and C_{min} = total and mineral (or inorganic) carbon content [$\mathrm{g\ g^{-1}}$], to be considered for calcareous soils, and if dry combustion is used with typically high temperatures (otherwise: C_{tot} equals C_{min})*
d = depth of horizon/depth class [m]
BD = bulk density [$\mathrm{kg\ m^{-3}}$]
$\mathrm{CF}_{\mathrm{st}}$ = correction factor for stoniness ((1- % stones)/100), including subtraction of gravel and stones

Equation 2: Determination of SOC stock of organic layers (e.g. forest floor layers)

$$\mathrm{SOC}_{\mathrm{forest\ floor\ stock}} = \mathrm{weightOR} * (C_{\mathrm{tot}} - C_{\mathrm{min}})$$

Where:
$\mathrm{SOC}_{\mathrm{forest\ floor}}$ = soil organic carbon in the forest floor [$\mathrm{kg\ m^{-2}}$]
weightOR = dry weight of the forest floor material sampled [$\mathrm{kg\ m^{-2}}$]
C_{tot} and C_{min} = total and mineral (or inorganic) carbon [$\mathrm{g\ g^{-1}}$], to be considered for calcareous soils, and if dry combustion is used with typically high temperatures (otherwise: C_{tot} equals C_{min}) †

†Values obtained by direct or indirect measurement, see Annex 1.

4.2.1.3 · IMPORTANT ELEMENTS TO CONSIDER IN SOC STOCK CALCULATIONS

Bulk density expresses the soil weight per unit volume (GSP Secretariat and ITPS, 2016), is the most important factor for estimating SOC stocks, and is mainly responsible for the differences between estimates. SOC stocks in areas with soils which are high in organic carbon are the most affected by the variability in BD (Hiederer and Köchy, 2011). Since SOC stock is a product of several factors, uncertainty (or errors in measurement) in one of the factors affects all others (see equations in Box 3). However, BD is among the most underestimated soil parameters when it comes to determination in the field. In many studies, information on either the method or the number of replicates used for BD determination is lacking, or BD is not measured and reported at all. Missing BD values impose a large uncertainty error on estimates of SOC stocks and SOC stock changes (Walter *et al.*, 2016). Consequently, measures to reduce the uncertainty in global SOC stocks should be directed to those soils that are associated with a large extent (area), high levels of organic C, low BD, or great depth (Köchy *et al.*, 2015). The following approaches may be used to derive BD (GSP Secretariat and ITPS, 2016; Laurenz and Lal, 2016):

1. BD could be measured after sampling.
2. Predicted using appropriate pedotransfer functions. However, pedotransfer functions have larger errors than estimation and measurement methods.
3. Use of default values from literature (i.e. IPCC Tier 1 or Tier 2 values).

Accounting for stoniness by subtracting stone content (including gravel) to determine the amount of fine earth is also crucial for accurate SOC stock calculation. The estimation of stoniness is difficult and time consuming, and therefore not carried out in many soil inventories, or only estimated visually in the profile (GSP Secretariat and ITPS, 2016). Instead of using a constant value, accurately determining the rock fragment BD is recommended when rock fragments dominate the total volume of the sample (e.g., in deeper soil depths) to reduce potential measurement errors (Laurenz and Lal, 2016). Approaches to derive the stone content include (GSP Secretariat and ITPS, 2016):

1. direct measurement from soil samples (weight of stones in a sample of known volume);
2. estimation during field work; and
3. cited values from literature (e.g. typical values per soil type and depth – Tier 1 and 2 approaches).

To date, there is no practical and robust method for estimating stone content. This needs to be developed to improve the accuracy of calculations (Laurenz and Lal, 2016), as slight over- or underestimations in the BD and stone content, and consequently the amount of fine earth can have a strong impact on the SOC stock estimates (GSP Secretariat and ITPS, 2016).

To avoid overestimation of SOC stocks, especially in stone-rich soils, a simpler calculation was recently proposed (Poeplau *et al.*, 2016):

$$SOCstock = d * (C_{tot} - C_{min}) * \frac{mass_{finesoil}}{volume_{sample}}$$

This calculation stresses that the sampled volume ($volume_{sample}$) should not be corrected dependant on stoniness, but the priority should be the accurate estimation of fine soil mass ($mass_{\text{fine soil}}$).

Finally, while according to the IPCC 2006 guidelines, the requested depth for GHG inventories is 30 cm, there is no scientific consensus on the soil depth to which measurements and estimates of SOC stock should be conducted (IPCC, 2006; Laurenz and Lal, 2016). It is well-known that land use and management is likely to have a major impact on deeper soil layers (IPCC, 2006).

4.2.1.4 · UPSCALING SOC DATA

National level data are needed in all GHG reports. Therefore, there is a need to upscale the available data from local to national scales. Different methods exist to do this and an overview of common upscaling methods is given in table 7 (GSP Secretariat and ITPS, 2016).

Table 7 · Overview of the main upscaling methods for SOC accounting.
Taken from GPS Secretariat and ITPS, 2016

Conventional upscaling	Class-matching	Derive SOC stocks per hectare per "class". This approach is used in the absence of spatial coordinates of the source data
	Geomatching	Point locations with spatial referencing are overlaid with GIS layers of important covariates.
Digital soil mapping (all methods require geomatching)	Data mining	Multiple regression, classification tree, artificial neural network
	Geostatistics	Regression kriging, kriging with external drift
	Knowledge-based systems	Fuzzy inference system, decision tree, Beyesian belief networks

4.2.1.5 · MONITORING SOC STOCKS CHANGES OVER TIME

Temporal changes in SOC stocks can be assessed either by repeated soil inventories, through monitoring programs on representative sites before and after land use and/or management changes, or by repeated soil sampling over regular time intervals when no such changes occurred (Laurenz and Lal, 2016). Soil properties that are responsive to management intervention can be monitored rather easily. SOC changes, however, which may also be affected by climate change, are subject to inter-annual variability due to the rotation of practices, as well as irregularity in the disturbance regime and the cycles in the climate variables. Hence, SOC stocks must be monitored over longer time periods. Moreover, SOC stock changes are small relative to the very large SOC stocks, as well as their inherent variability across space and time, which requires sensitive measurement techniques and due consideration for the minimum detectable differences, as well as representative sampling design and size. Therefore, monitoring protocols must be designed to detect changes in soil properties over relevant spatial and temporal scales, with adequate precision and statistical power. For example, the effect of climate change on SOC is observed more readily at a broad scale than at a smaller spatial scale (Batjes and Van Wesemael, 2014).

Continuous monitoring of SOC at time intervals of 10 years is recommended. It can be a compromise between detectability of changes and temporal shifts in trends. However, this is longer than the duration of many land use and management projects that involve the measurement of SOC stock changes (i.e. for the baseline and at the end of the project). Some countries use an interval of 5 years (Batjes and Van Wesemael, 2014).

4.2.1.6 · SOIL MONITORING NETWORKS (SMN)

Within soil monitoring networks (SMNs), information on direct changes of SOC stocks can be provided through repeated measurements at a given site, as well as data to parameterize and test biophysical models at plot scale. SMNs must be designed to detect changes in soil properties over relevant spatial and temporal scales, with adequate precision and statistical power. Most SMNs, however, are in the planning or early stages of implementation; few networks are located in developing countries, where most deforestation and land use change is occurring. Within these monitoring networks, sites may be organized according to different sampling schemes, for example regular grid, stratified approach or randomized sampling, Adequate statistical methods should be associated with each of these sampling designs (Batjes and Van Wesemael, 2014). Examples of national SMNs are listed in Annex 2 (non-exhaustive list).

4.2.2 · CHALLENGES IN MEASURING AND MONITORING SOC

Firstly, annual changes in SOC are small compared to the SOC stocks, and these stocks are highly variable throughout the landscape. Changes in the carbon balance attributable to projects can only be detected after 5–10 years (FAO, 2015). Secondly, the suitability of existing data for monitoring changes in SOC stocks is uncertain. There is currently a great need for revised methodologies including those for soil sampling, and updated remote sensing and field information to enhance the credibility of the overall data (Laurenz and Lal, 2016). Globally, to enable a SOC monitoring program to represent the main types of ecosystems and allow both the SOC stocks and the stock changes to be estimated, several challenges remain to be solved:

1. **Harmonization:** As the information on SOC is geographically unbalanced, an immediate challenge is the harmonization of existing regional soil monitoring programs and soil databases (Batjes and Van Wesemael, 2014; Jandl *et al.*, 2014; GSP Secretariat and ITPS, 2016). Harmonization refers to the minimization of systematic differences between different sources of environmental measures (Batjes and Van Wesemael, 2014).

2. **Universal metric:** The identification of a universal metric for SOC monitoring is needed. Typically, information is available for the total C content, which is then converted to the total SOC pool (Jandl *et al.*, 2014).

3. **Universal spatial and temporal resolution:** adoption of a scientifically and politically (e.g. for UNFCCC) appropriate spatial and temporal resolution for the measurement of SOC, as well as consistent global protocols are eventually needed (Batjes and Van Wesemael, 2014).

4. **Soil depth measure:** A standardized approach to the reported soil depth for SOC pool estimations is required, since SOC can be unevenly distributed over varying soil depths (Jandl *et al.*, 2014; Laurenz and Lal, 2016).

5. **Field protocols and sampling:** Specific fieldwork protocols and efficient sampling systems for the assessment of SOC dynamics are needed. The large spatial heterogeneity of SOC in comparison to its moderate temporal change calls for cost-effective sampling protocols in order to properly capture SOC dynamics on a landscape scale and to identify small SOC changes in a highly variable pool (Batjes and Van Wesemael, 2014; Jandl *et al.*, 2014; Laurenz and Lal, 2016).

6. **Need to include SOC in soil experiments:** SOC monitoring programs need to liaise with long-term soil experiments that offer a baseline for the SOC pool and can comprise a set of sites where targeted research on soil processes and their impacts on SOC can be performed (Jandl *et al.*, 2014).

7. **Improved understanding:** The understanding of SOC stabilization processes is incomplete. There is no general agreement on SOC fractionation methods to estimate the degree of stabilization achieved (Jandl *et al.*, 2014).

4.2.3 · VERIFICATION OF SOC STOCK ESTIMATES

The Quality control and Quality assessment (QA/QC) process contributes to improve the transparency, consistency, completeness, accuracy and therefore comparability of GHG inventories. The QA/QC process is part of the internal verification process. QA is a planned system of review procedures conducted by third parties not directly involved in the monitoring/reporting process. Reviews are performed on a completed inventory using QC procedures. Reviews verify that measurable objectives are met, ensure that the inventory represents the best possible estimates of emissions and removals given the current state of scientific knowledge and data availability, and support the effectiveness of the QC programme. QC activities include general methods such as accuracy checks on data acquisition and calculations, and the use of approved standardized procedures for data collection, emission and removal calculations, including associated uncertainties, data archiving and reporting. (IPCC, 2006).

Regarding data collection (i.e. measurements), SMNs should be included in a broader cross-method validation programme to ultimately enable spatially and temporally validated comparisons both within and between countries (Batjes and Van Wesemael, 2014). Finally, verification according to the IPCC involves the comparison of National GHG Inventory estimates with alternative estimates, and is also a mean to ensure the quality of estimates prepared (IPCC, 2006). A summary of the MRV process with the framework of SOC is given in Figure 12.

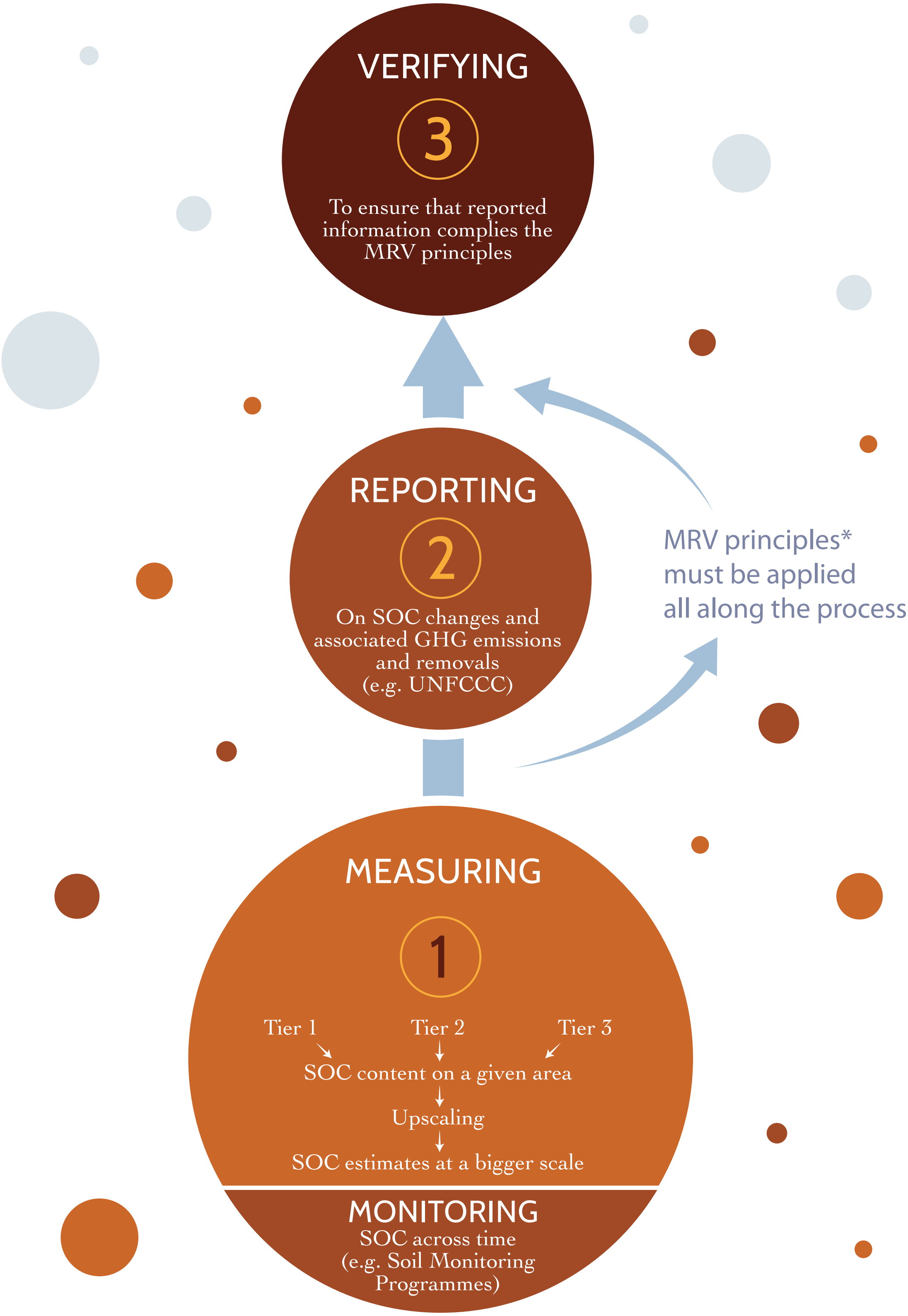
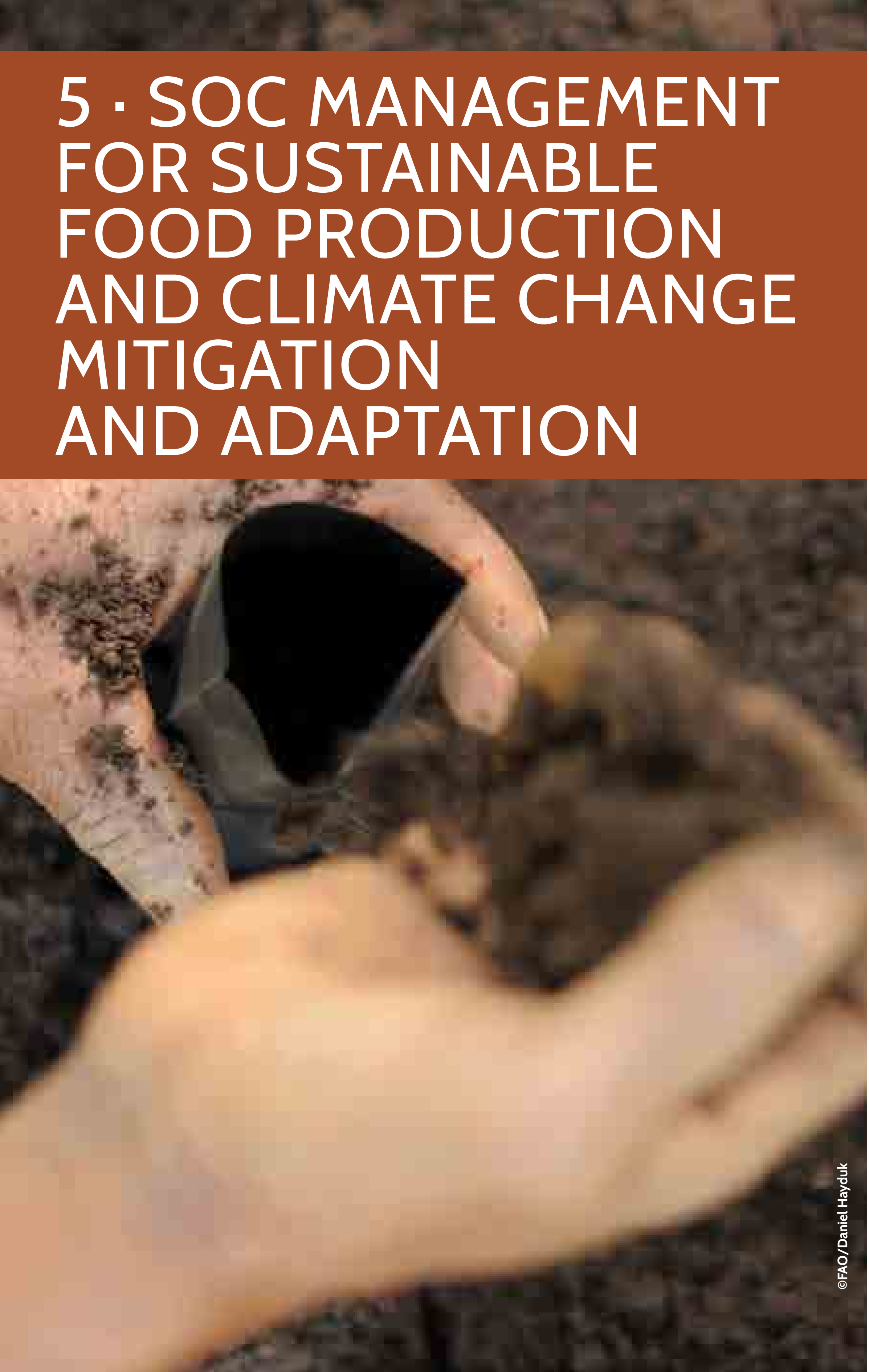


Figure 12 · Summary of the SOC Measurement, Reporting and Verifying (MRV) Framework.

*MRV principles: Accuracy, consistency, completeness, comparability and transparency (See section 4.1.1)

5 · SOC MANAGEMENT FOR SUSTAINABLE FOOD PRODUCTION AND CLIMATE CHANGE MITIGATION AND ADAPTATION



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5.1 · SOC MANAGEMENT FOR SUSTAINABLE FOOD PRODUCTION

It has been widely recognized that SOC sequestration can be of great importance as a climate change mitigation and adaptation measure. However, it is often forgotten that SOC (as a proxy for SOM) plays an equally important role in ensuring food security. This is achieved by enhancing soil productivity and maintaining consistently high yields, particularly by increasing water and nutrient holding capacity and improved soil structure, thus improving plant growth conditions (Zdruli *et al.*, 2017)

Climate change is likely to have a strong impact on agriculture, thus posing a major threat to food security (FAO, 2015). IPCC's projection of a 4 °C temperature increase until the end of the 21st century is thought to cause devastating repercussions for food security given the increasing global food demands (IPCC, 2007). In fact, climate change is one of the major challenges that the world's agricultural sector faces in meeting the global food requirements. Food security in relation to climate change is affected in four different dimensions (FAO, 2015):

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

Climate change, as evidenced by increasing temperatures, changing precipitation patterns and more frequent and extreme weather events, tremendously impact crop and livestock production. Furthermore, increasing water body temperatures, decreasing pH levels and changes in current sea productivity patterns most affect fisheries production. Consequently, major drawbacks are expected which include yield reductions, biological migration, declines in agrobiodiversity and ecological services, loss of agricultural incomes, and increases in food prices and trading costs (FAO, 2015). Therefore, there is a drive to hone measures that alleviate the risks affecting global food security. As vital as it is for climate change mitigation and adaptation, SOC is key for ensuring a consistent global food supply.

Soil organic carbon content is one of the key soil properties associated with many soil functions. It is a source of nutrients and is crucial for agricultural production. Increases in SOC stock increases crop yields in high-input commercial agriculture, but especially in low-input degraded land. In areas like Sub-Saharan Africa (SSA), where subsistence farmers experience deficiencies in fertilizer availability and proper irrigation, SOC is the key for increased production (Lal, 2004). Many studies have quantified the contributions of SOC in terms of food production. De Moraes Sá *et al.* (2017) reported that adoption of SOC conserving agricultural practices can increase food production by 17.6 Mt/year. Lal (2004) specified that a 1 tonne increase in the SOC pool of degraded cropland can increase wheat yields by 20-40 kg ha^{-1}, maize by 10-20 kg ha^{-1}, and cowpeas by 0.5-1 kg ha^{-1}. Therefore, sustainable soil management that increases SOC stocks should be developed on a local and global basis, and should be adopted for more sustainable food systems.

5.2 · SOC MANAGEMENT FOR CLIMATE CHANGE MITIGATION AND ADAPTATION

Climate change mitigation refers to efforts aimed at restraining, halting and/or reversing climate change through management strategies, behavioral changes and technological innovations that reduce the emission of GHGs. CO_2 is one of the most emitted GHGs through human activities in today's era (Kane, 2015). With proper proactive mitigation practices, soils can play an integral role in reducing CO_2 emissions due to their carbon sink potential (Lal, 2004). Benefits arising from such mitigation actions tend to be global and long term (IPCC, 2007).

Climate change adaptation, on the other hand, refers to efforts aimed at achieving higher resilience towards unprecedented climatic events and conditions. It implies the anticipation of climate change and its adverse effects, and strives to manage them through appropriate actions that minimize the associated risks and negative impacts. To put it simply, they are actions that help human and natural systems adjust to a changing climate (IPCC, 2014). Contrary to mitigation, adaptation measures can be both reactive and proactive, and benefits presented are usually local and shorter term (IPCC, 2007). Adaptation measures can often involve soil: in an attempt to overcome vulnerability and create resilience against extreme weather conditions such as storms, floods and droughts, healthy and properly managed soils are able to act as a buffer. For example, soils with an optimal SOC content can absorb and store water under extensive rain, and make it available for vegetation under drought conditions. Healthy soils can provide proper aeration and a consistent supply of oxygen that can impede any further carbon emissions resulting from methanogenesis (FAO and ITPS, 2015).

Mitigation and adaptation measures both offer solutions that respond to climate change which can be related to the sustainable development goals. However, they are not always considered complementary on a local scale; sometimes they are substitutable, competitive/conflicting or independent from each other. For instance, some adaptation measures to climate change, such as optimized fertilization and irrigation, have a high energy demand and may hence contribute to even higher CO_2 emissions. On the other hand, adaptation may never be a perfect substitute for mitigation since the latter will always be needed to avoid even larger changes in the climate system. Currently, due to already present warming, adaptation measures are nevertheless required despite the higher associated financial costs, regardless of the scale of mitigation efforts (IPCC, 2007).

Given the role of soils in climate change mitigation and adaptation and the limitations presented by SOC saturation in sequestering additional carbon inputs, judicious soil management needs to be implemented to ensure that a soil is rendered a sink rather than a source for atmospheric CO_2 (Paustian *et al.*, 2016). Therefore, it is ideal to study and determine, for any given ecosystem, both the current SOC stocks and the respective carbon saturation point to determine a soil's carbon sequestration potential. Only then will it become possible to achieve maximum efficiency of SOC sequestration through adaptive management strategies. Figure 13 shows recommended and dissuaded management strategies that foster SOC for optimal food production and climate change mitigation and adaptation. These practices address the above challenges through a number of mechanisms that aim to: increase photosynthetic and SOC sequestration potential (i.e. through afforestation, reforestation and cover cropping); decrease GHG emissions and SOC losses (i.e. through conservation/reduced tillage and organic farming); and increase food production by improving soil properties for better water, nutrient and pH buffering capacity (i.e. by adding organic amendments such as compost and biochar).

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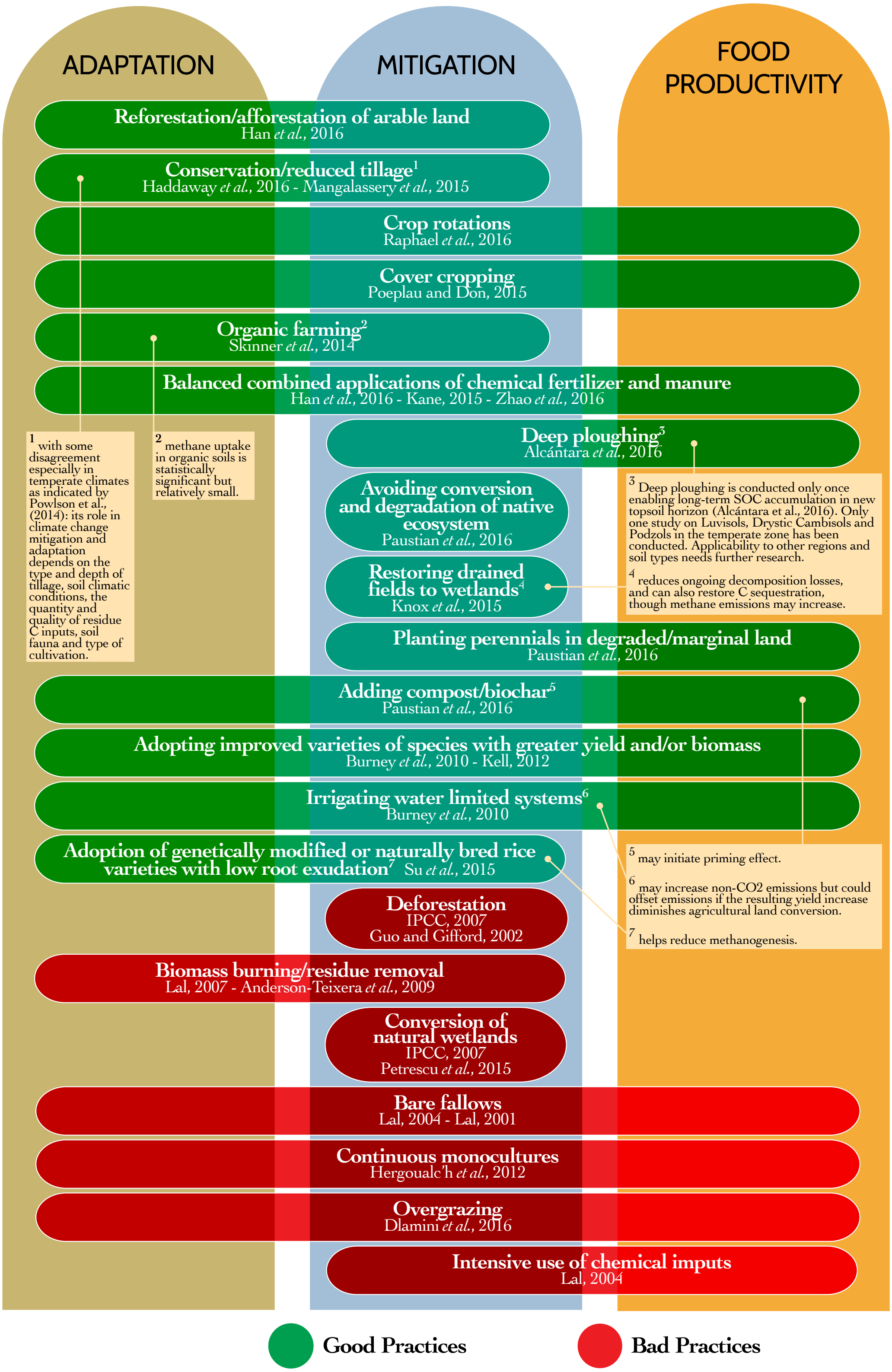

[1] with some disagreement especially in temperate climates as indicated by Powlson et al., (2014): its role in climate change mitigation and adaptation depends on the type and depth of tillage, soil climatic conditions, the quantity and quality of residue C inputs, soil fauna and type of cultivation.

[2] methane uptake in organic soils is statistically significant but relatively small.

[3] Deep ploughing is conducted only once enabling long-term SOC accumulation in new topsoil horizon (Alcántara et al., 2016). Only one study on Luvisols, Drystic Cambisols and Podzols in the temperate zone has been conducted. Applicability to other regions and soil types needs further research.

[4] reduces ongoing decomposition losses, and can also restore C sequestration, though methane emissions may increase.

[5] may initiate priming effect.

[6] may increase non-CO2 emissions but could offset emissions if the resulting yield increase diminishes agricultural land conversion.

[7] helps reduce methanogenesis.

Figure 13 · Suggested and dissuaded management strategies for soil carbon sequestration and their impact on food productivity and climate change mitigation and adaptation.

Colours indicate good (green) and bad (red) practices. Partially adapted and modified from Ogle *et al.*, 2014, and Descheemaeker *et al.*, 2016

5.3 · CHALLENGES OF SOC SEQUESTRATION

The challenges of SOC sequestration and preservation are manifold. Some are caused by human induced factors such as low adoption rates of sustainable soil management practices, the reasons for which are diverse (FAO and ITPS, 2015). Others are related to abiotic factors and are beyond human control. In this section, the different barriers to the adoption of relevant measures and the abiotic factors that hinder SOC sequestration are discussed.

5.3.1 · BARRIERS TO ADOPTION OF CLIMATE CHANGE MITIGATION AND ADAPTATION MEASURES

5.3.1.1 · FINANCIAL BARRIERS

Financial barriers are one of the key barriers that restrict the implementation of adaptation strategies (Antwi-Agyei, 2012; Antwi-Agyei *et al.*, 2015; Takahashi *et al.*, 2016; Azhoni *et al.*, 2017). In fact, every form of climate change adaption and mitigation practice entails some direct and/or indirect financial cost (Takahashi *et al.*, 2016). An example of a direct climate change adaptation cost would be the use of expensive improved crop varieties that offer tolerance to unfavourable growing conditions or the application of off-farm, carbon-rich inputs. Indirect costs, on the other hand, include practices with high opportunity costs which require an investment of time that might otherwise be directed to income producing activities (Boon, 2013) (e.g. incorporating crop residues into soil versus tending to crops or selling them as biomass).

Financial barriers which may discourage farmers from implementing SOC-building practices can be in the form of budget deficits or limited finances and access to capital at farm, provincial, or national level (UN-HABITAT, 2010; Takahashi *et al.*, 2016). Others include high currency risk due to fluctuation of foreign exchange rates; upfront investment costs such as those for equipment, machinery and labour; opportunity costs of household assets; costs associated with time and travel to access technical advice or inputs; and potentially low-returns given by the uncertainty of the likely benefits (FAO, 2015). In fact, in a study done by Takahashi *et al.* (2016) on the barriers that farmers experience in undertaking climate change adaptive measures, the most frequent response pertained to economic consideration, particularly the relative economic risk of implementing a new practice or the unpredictability of changing market conditions as it relates to climate change. Therefore, finance is considered a main driver of farmers' practices (Takahashi *et al.*, 2016).

5.3.1.2 · TECHNICAL AND LOGISTICAL BARRIERS

Notwithstanding the fact that technological developments such as new crop varieties, soil conserving machinery, and irrigation systems are considered to be one of the key agricultural climate change adaptation and mitigation pathways (Smit and Skinner, 2002), missing technology is often one of the barriers to adoption of mitigating and adaptive measures (FAO, 2015). These barriers to adoption are especially pronounced in least developed regions such as in SSA (Kithiia, 2011; Antwi-Agyei, 2012) where farmers have little to no access to such tools (Kolikow *et al.*, 2013). As such, these limitations may constrain opportunities for farmers to achieve agricultural resilience and enhance food security through mitigation and adaptation practices that foster SOC sequestration (Antwi-Agyei, 2012).

Technical barriers can occur in many forms including non-availability of appropriate technologies, technical capacity and/or equipment, and low detectability of short-term changes such as those encountered during periodic measurements of SOC dynamics (FAO, 2015). Logistical barriers have been reported as the difficulty and complexity of making adaptations to long-term climate trends due to the high year-to-year variability, especially given the high risk of short-term failures and the unviability of adaptive practices from one year to another (Takahashi *et al.*, 2016).

5.3.1.3 · INSTITUTIONAL BARRIERS

Institutions such as governments have the power to raise or remove barriers, and can act either as an enabler of, or an obstacle to implementing climate change adaption and mitigation measures (Agrawal and Perrin, 2009; Biesbroek *et al.*, 2013). For instance, low adoption rates of climate change mitigation and adaptation practices in many SSA countries can be attributed to their inefficiently bureaucratic government policies which often constrain adaptive strategies at the regional and local levels (Sietz *et al.*, 2011; Antwi-Agyei, 2012). As such, institutional barriers can take the form of national policy regulations, but also insecure land tenure; imperfect markets and low risk-taking capacity; limited research and extension services; weak inter-institutional coordination; gender-related cultural conventions; and an emphasis only on mitigation benefits without considering benefits that are not related to climate change (FAO, 2015).

On-farm decision making and farming practices are largely driven by the available markets and the operation's business model (Antwi-Agyei *et al.*, 2015). For example, farmers perceive that due to their long term pre-established links to specific markets, finding new markets for new crop or new hybrids or varieties that sequester more carbon in the soil is a difficult task, as it is unlikely that a farmer would switch crops or intercrop unless there was a guaranteed market (Takahashi *et al.*, 2016). A lack of readily available markets, however, can also include poor physical infrastructure development such as road networks or the absence of appropriate storage facilities for certain crops. This particularly discourages adoption as it weakens the bargaining power of many small-scale farmers who cannot store their harvest on their farms if they choose to do so when market prices are low (Antwi-Agyei *et al.*, 2015).

Furthermore, in many smallholder farming communities, especially in developing countries, the only link farmers have to knowledge-based assets and technological innovations on sustainable soil management is through extension services. Since the role of extension officers is to facilitate and transfer scientific ways of farming, they are often found overwhelmed by the number of communities they are responsible for. This impedes the efficacy of attending to the needs of all farmers and hampers the adoption of soil conserving practices. Therefore, weak institutional capacity leads to lack or the unreliability of climate adaptation information which, combined with weather variability, will place food security in many developing countries under considerable stress (Antwi-Agyei, 2012).

5.3.1.4 · KNOWLEDGE BARRIERS

Knowledge barriers in the form of lack of information or awareness is one of the major obstacles to reducing land degradation, improving agricultural productivity, and facilitating the adoption of sustainable land management among smallholder farmers (Liniger *et al.*, 2011). In developing countries, the lack of state-of-the art equipment at meteorological departments translate into poor information on weather conditions, resulting in farmer's low adoption of management strategies that mitigate and adapt to climate change (Antwi-Agyei, 2012). It is important to note that reliable climate information such as annual forecasts is equally important for food security, given that many farming systems globally depend on rain-fed agriculture, and seasonal forecasts may not be the best option for long-term planning of agricultural activities (Ziervogel *et al.*, 2010). Sufficient knowledge of the different available options is also crucial for farmers to make informed decisions on the best management strategies (Lee, 2007).

A significant aspect in relation to the knowledge barrier is that in some cases, it's not as much about what knowledge is being transmitted to the farmer, rather than who is transmitting it. In a survey conducted by Takahashi *et al.* (2016), many surveyed farmers expressed skepticism about the accuracy of information from certain sources, namely those that are politically affiliated, and highlighted the need for access to information from reliable, consistent, objective and apolitical sources. It is generally desirable and even expected that farmers be a part of panels or commissions on sustainable soil management and for policy formation, since farmers themselves, along with cooperative extension agents, are deemed the most reliable sources for local information (Takahashi *et al.*, 2016).

5.3.1.5 · RESOURCE BARRIERS

Resource barriers can be seen as the absence of sufficient land, labour, inputs, water and/or plants available to begin adapting to and mitigating climate change (Takahashi *et al.,* 2016). In one study, the greatest obstacle to improving soil functions and other ecosystem services in SSA was identified as the lack of plant residues produced due to the low productivity of the soils (Palm *et al.*, 2014). In terms of labour for example, many farmers, especially in developing countries, rely on off-farm work as an additional source of income, which in turn limits the amount of time they spend working on their farms implementing innovative and sustainable soil management practices (Takahashi *et al.*, 2016).

5.3.1.6 · SOCIO-CULTURAL BARRIERS

Social barriers are one of the key barriers that influence people's actions for dealing with climate change mitigation and adaptation (Antwi-Agyei *et al.*, 2015), and can be cognitive or normative (Swim *et al.*, 2011). Antwi-Agyei *et al.* (2015, p.19) stated that "the belief systems of a particular group of people can constitute one of the greatest barriers to the implementation of climate adaptation strategies". The voluntary implementation of sustainable soil management practices largely depends on the way farmers perceive climate change and the identification of risks which is fundamentally influenced by personal beliefs, cultural norms, value systems and worldviews (Jones and Boyd, 2011; Smith *et al.*, 2011; Antwi-Agyei, 2012; Adger *et al.*, 2013). As such, different cultural groups with distinct pre-existing belief systems within the same geographical region may respond differently to risks generated from climate change (Moser, 2010; Adger *et al.*, 2013).

The interconnectedness of barriers

The different barriers to adoption of climate change adaptation and mitigation practices are highly intertwined, amplifying the challenges of fostering SOC sequestration. For example, technical and logistical barriers are highly connected and related to financial, socioeconomic, and institutional constraints (Klein *et al.*, 2001). This can be exemplified by the lack of sufficient funds for a government agency or the absence of a proper structure that enables efficient reporting which will most likely translate into technical, logistical and knowledge constraints. Furthermore, financial barriers are highly correlated with institutional barriers. In particular, insufficient credit facilities are considered one of the most important obstacles hindering the implementation of appropriate management strategies by farmers, e.g. in Ethiopia (Bryan *et al.*, 2009). It is also clear that the lack of readily accessible markets as an institutional barrier further solidifies financial barriers. The absence of markets fuels the vicious cycle that links low prices for agricultural products to the inability to repay loans, preventing the acquisition of future loans and resulting in low adoption rates of sustainable land practices (Antwi-Agyei *et al.*, 2015).

In some cases, different barriers to adoption of climate change mitigation and adaptation strategies may be overcome using a number of approaches. Box 4 contains a list of recommended tactics to overcome some of these barriers.

BOX 4 · PROPOSED SOLUTIONS TO OVERCOME BARRIERS

- Financial barriers may be overcome through financial incentives or regulations that account for local conditions, including incentives provided by local markets (FAO and ITPS, 2015).
- Socio-cultural barriers may be overcome for adaptation strategies that acknowledge local context such as belief systems and indigenous knowledge (Jennings and Magrath, 2009).
- Knowledge barriers can be overcome through policies that maintain climate monitoring and that ensure effective and consistent communication of information (Easterling *et al.*, 2003; Howden *et al.*, 2007). This can also be achieved by strengthening policies that support all stakeholders that provide relevant climate information from research, analytic systems, extension services, industry and regional networks (Howden *et al.*, 2007).
- Technical and logistical barriers may be overcome by making available existing technologies for implementing sustainable soil management and investing in new technical or management strategies such as improved varieties. Policies that maintain the capacity to make continuing adjustments and improvements in knowledge-based assets through “learning by doing” via targeted monitoring of climate change mitigation and adaption practices and their costs, benefits, and effects should also be established (Burton and Nations, 2005; Howden *et al.*, 2007).
- Institutional and resource barriers may be overcome by developing new infrastructure (e.g. irrigation structures, efficient water use technologies, transport and storage systems, revising policies (land tenure arrangements, property rights), and establishing accessible, efficient markets for products and inputs (e.g. seed, fertilizer, labour, etc.) and for financial services, including insurance (Turvey, 2001; Howden *et al.*, 2007).

5.3.2 · NON-HUMAN INDUCED FACTORS LIMITING SOC SEQUESTRATION: ABIOTIC FACTORS

In addition to human-induced barriers, uncontrolled abiotic factors such as climatic conditions and soil texture can limit the soil's potential to sequester carbon, particularly by influencing carbon cycling processes mediated by soil biota (FAO and ITPS, 2015). Warmer temperatures in northern latitudes accelerate SOC decomposition which is observed by the high CO_2 fluxes occurring during the summer when biological processes are promoted. Consequently, maintaining SOC stocks may be more challenging under such conditions. SOC sequestration rates in agricultural and restored ecosystem soils are estimated to range from 0 to 150 kgC ha^{-1}/year in warm and dry climates, compared to 100 to 1 000 kgC ha^{-1}/year in humid and cool climates (Lal, 2001). This can be explained by the fact that, during the winter months or in cold climates, low CO_2 fluxes are observed since low temperatures suppress decomposition processes (Ward *et al.*, 2007; Clark *et al.*, 2009; Armstrong *et al.*, 2015). However, during extreme events such as drought, SOM decomposition may initially decrease, but may subsequently increase after rewetting (Borken and Matzner, 2008). Although it is well established in soil C cycle models that temperature is a major control of SOM storage, the temperature sensitivity of decomposition of different SOM fractions remains an area of uncertainty (Conant *et al*., 2011).

Water also influences SOC storage through several processes. Since well-aerated, moist soils are optimal for microbial activity, decomposition rates decrease as soils become drier. In contrast, organic matter decay rates are decreased in flooded soils due to restricted aeration, often yielding soils with very high amounts of SOC (e.g. peat and muck soils) (FAO and ITPS, 2015). In these water-saturated soils, other abiotic properties, namely physical properties such as peat depth and bulk density also influence the biological processing of C cycling. These properties control, for example, substrate availability and the diffusion rates of water, compounds, and gas through the peat profile, ultimately influencing the SOC in the soils (Dorrepaal *et al*., 2009; Levy *et al*., 2012). However, such flooded conditions may cause a surge in CH_4 emissions (Blodau *et al.,* 2004). In terms of CH_4, Armstrong *et al.* (2015) showed that there is a peak in CH_4 emissions from peat soils, especially in autumn (characterized by relatively high water tables and temperatures), which promoted greater methanogenesis (CH_4 production) while limiting methanotrophy (CH_4 oxidation).

In mineral soils, the quantity and composition of SOC is strongly dependent on soil type which can differ at the field-scale. In clay-rich soils, higher organic matter content and a higher concentration of O-alkyl C derived from polysaccharides may be expected. On the contrary, sandy soils are often characterized by lower C contents and high concentrations of alkyl C (Rumpel and Kögel-Knabner, 2011), thereby decreasing its potential for increasing SOC stocks. Other abiotic barriers to SOC sequestration may include soil erosion and fires which may initially decrease soil C storage (Knicker, 2007).

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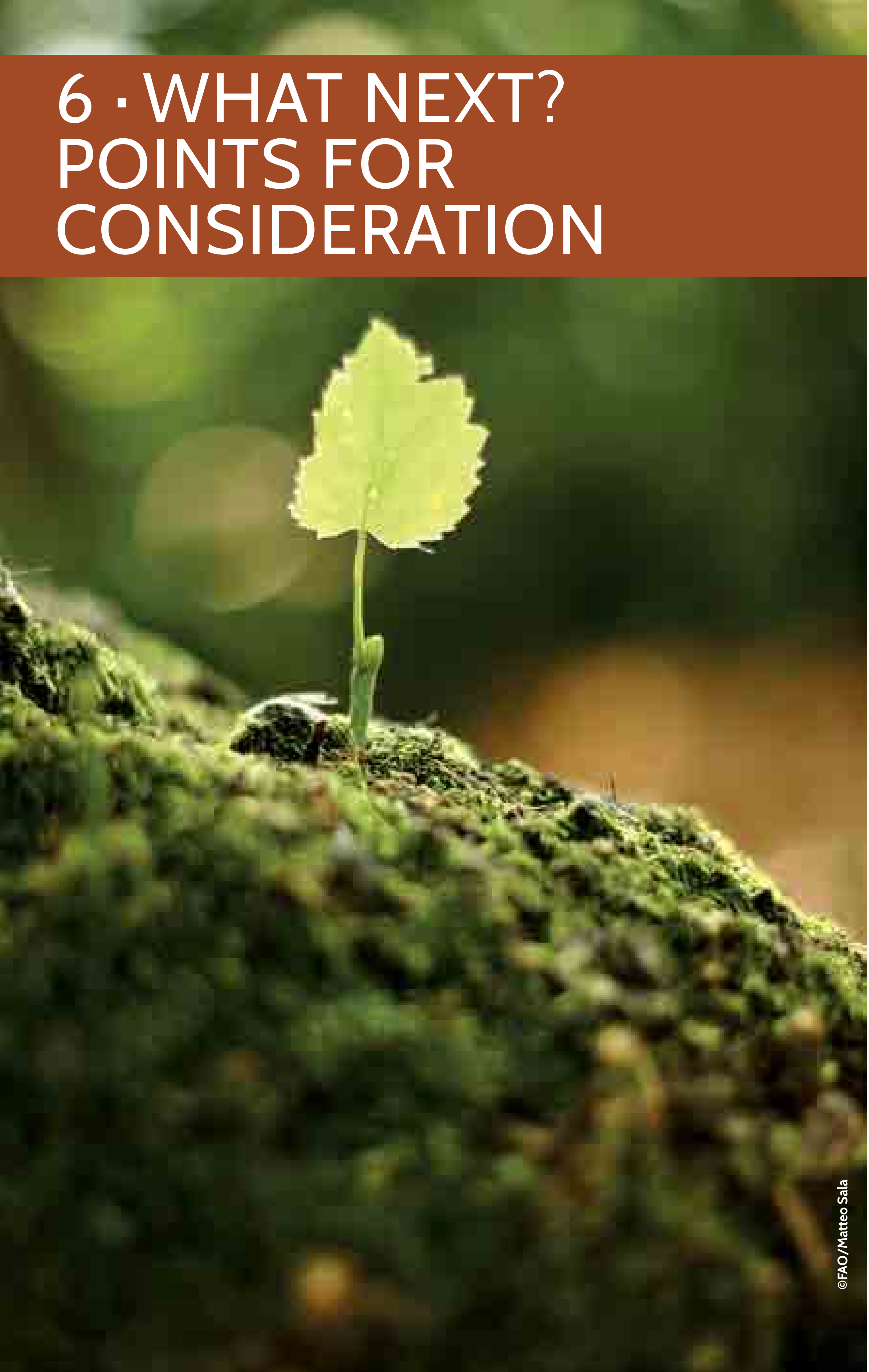
6 · WHAT NEXT? POINTS FOR CONSIDERATION



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SOC CYCLE...

- The full scope of the global carbon cycle and its interdependency on SOC dynamics and relation to other biogeochemical cycles is yet to be fully understood. More accurate SOC measurement, mapping, monitoring and reporting can contribute to achieving progress in this regard.
- Land management practices and systems that foster SOC sequestration should aim to retain carbon in the soil over the long-term. The SOC saturation threshold remains a theoretical concept requiring site specific information on the amount of additional SOC that can be sequestered and the way to achieve.

FOOD SECURITY AND CLIMATE CHANGE...

- There is a need for improved knowledge and immediate action to efficiently manage SOC to improve food production and climate change mitigation and adaptation, as well as contribute to achieving the SDGs by 2030.
- Accurate prediction of the impact of human activity on climate change is currently limited, especially due to an incomplete understanding of soil respiration and uncertainties concerning the priming effect, microbial contributions to carbon feedback, or the adaptation of microbial communities.
- Identification of SOC hot-spots and improved understanding of their potential to mitigate climate change is needed to raise awareness on the necessity to sustainably manage them.

SOC STOCK AND ASSESSMENT OF SOC STOCK CHANGES...

- Many of the currently available maps and global SOC estimates are based on historic databases, rather than current or recent monitoring. A new compilation of country-specific SOC stocks is necessary to develop national baselines for SOC in support achievement of SDGs and assessments related to the effects of climate change.
- Innovative methods that enable the frequent and cost-effective monitoring of SOC stocks need to be established in all countries. It remains difficult to accurately calculate SOC stocks, especially due to the difficulty in measuring the parameters bulk density and stone content.
- Reporting on the status and trends of SOC based on measurements is a challenging task which needs to be tackled through harmonized methodologies, the use of standardized sampling and modelling techniques, harnessing innovative solutions to data collection and sharing, and considering different field practices implemented at different scales.

MANAGEMENT...

- Well founded and research-based recommendations for maintaining and/or increasing SOC stocks through judicious management practices at different scales are crucial for all land use types, especially in hot-spots and bright spots.
- Better, more holistic and comprehensive ways to overcome barriers to adoption of SOC sequestration practices are necessary for policy design and implementation.

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ANNEXES

ANNEX 1: MAIN METHODS FOR SOC CONTENT DETERMINATION

Compiled from Laurenz and Lal, 2016; GSP Secretariat and ITPS, 2016; Pallasser, 2013; Chatterjee *et al.*, 2009.

Method type	Name		Advantages	Disadvantages
Analytical	Dry combustion	Automated Carbon analyser	• Current standard • Currently the most reliable • Rapid • Simple	• Separate measurement of organic and total soil carbon only rarely available (only for new element analysers that do a two-step combustion) • Requires a large number of samples • Expensive • High energy use • Interference from carbonates
		Loss-on -ignition	• Previously widely used • Easy-to-apply method • Inexpensive	• Not reliable due to reactions not related to OM (e.g. interference from carbonates or inter-lattice water) • Overestimates the organic matter content (likely to account for oxides and carbonates due to high temperatures) • SOC derived from SOM with a conversion factor (0.58) which is known to be incorrect for organic layers
	Wet combustion	Walkey-Black	• Previously widely used • Inexpensive • Quick approximate assessment • Selectively targets OM pools • Little interference from carbonates	• Destructive • Incomplete oxidation: correction factor needed • Tend to underestimate SOC • Interference from chlorides, and oxides of Mn^{2+} and Fe^{2+} • Needs harmful chemicals

Method type	Name	Advantages	Disadvantages
Remote Sensing	Space-borne or air-borne	• Use over large areas • Non-destructive	• Limited sampling depth • Surrogate indices needed
Spectroscopy	Infrared absorbance or reflectance spectroscopy: visible and near-infrared (Vis-NIR) and mid-infrared (MIR) spectroscopy	• Precise and accurate (less accurate in the visible region) • Rapid • Cost-effective • Non destructive • Use in laboratory or in the field • High through-put • Potential for remote-sensing • Enables high density sampling • Powerful analytical technique	• Continual need for calibration à Relatively large number of samples needed • Soil moisture can limit the accuracy • Appropriate, correct and matching reference laboratory data needed • Inability to deal directly with interferences from non-SOC components in samples of unknown origin • Chemometrical analysis needed
	Laser-induced breakdown spectroscopy (LIBS)	• Precise (up to 1 mm resolution) and accurate • High through-put • Potential use in-field • Rapid analysis	• Invasive • Expensive • Still developmental • Measures total soil carbon • Presence of roots and rock fragments may cause C signal variability • No universal calibration curve • Health hazards • Interference from carbonates, iron and water
	Inelastic neutron scattering (INS)	• Precise and accurate • Non-destructive (no soil removal, no ablation, no combustion) • In-field analysis • High potential for the future of soil C determination	• Expensive • Still developmental • No separate measurement of SOC and Soil Inorganic Carbon • Better results for C-rich soils • Health hazards • Interference from carbonates

ANNEX 2: EXAMPLES OF CURRENT NATIONAL SOC MONITORING SYSTEMS (NON-EXHAUSTIVE)

Country (Reference)	Region covered	Site selection[1]	Soil sampling[2]	Sub-samples depths (cm)	Sampling dates
Germany *(Arrouays et al., 2008 ; Batjes and Van Wesemael, 2014)*	Cropland and grazing land Also Walter, *et al.*, 2016	Grid	Composite	0-10, 10-30, 30-50 and 50-70 and 70-100	- First sampling in 1986 - Every 10 years
	Forest soils (BZE) Also Thunen Institute, 2016	Grid	Composite	0-5, 5-10, 10-30, 30-60, 60-90 cm; if possible 90-140 cm and 140-200cm	- First BZE Inventory 1987-1993 - Last resampling 2009-2016
Mexico *(Batjes and Van Wesemael, 2014)*	Forest and non-forest land (especially pasture and shrubs)	Grid	Composite	0-30 and 30-60 cm	- Started in 2003 - Every 5 years (each year 20% of the sites will be resampled)
New Zealand *(Sparling et al., 2004; Batjes and Van Wesemael, 2014; Stevenson et al., 2015)*	All regions	Stratified (700 sampling sites)	Single	Variable, sampled by soil horizon; in 2009 1 235 samples to 30cm	- First sampling in 1978 - Sampling ended in 2009
Sweden *(Arrouays et al., 2008 ; Batjes and Van Wesemael, 2014; Poeplau et al., 2015)*	Cropland (about 3 Mha)	Grid	Composite	0-20 cm topsoil and 40-60 cm subsoil. In 2003: 500 samples 0-20, 20-40 and 40-60 cm	- First inventory 1983-1988 - To be repeated every 10 years - New inventory ongoing

Country (Reference)	Region covered	Site selection[1]	Soil sampling[2]	Sub-samples depths (cm)	Sampling dates
France (RMQS) *(Jolivet, et al., 2006)*	All regions	Grid	Composite	0-30 (Cropland: 0-smallest depth of ploughing), 30-50 (cropland: 30-deepest depth of ploughing) cm	• First inventory 2001-2006 • To be repeated every 10 years • Forest survey since 1995
England and Wales (National Soil Inventory) *(Arrouays, et al., 2008)*	All regions	Grid	Composite	Fixed depth 0-15 cm	• First inventory 1966-1987 • From 7 to 37 years
Scotland (National soil Inventory of Scotland) *(Arrouays, et al., 2008)*	All regions	721 monitoring sites	Single	Pedological horizon, to 100 cm	• First inventory 1970-1980 • Last resampling 2007-2010
Switzerland (NABO) *(Schweizerische Eidgenossenschaft, 2015)*	All regions	103 sampling sites	4 composite samples from 25 single samples out of a 10x10m surface	0-20 cm, since 2005 20-40cm, since 2010 down to 100 cm	• NABO started 1985 • To be repeated every 5 years
Hungary (TIM) *(Arrouays, et al., 2008; Uveges, 2015)*	All land uses	Stratified (1 236 sampling sites)	1 composite sample out of 9 point sample	0-30, 30-60, 60-90 cm (pedological horizon up to 150 cm for forest soils)	• TIM started in 1992 • To be repeated every 3 years

[1] Stratified sampling involves dividing the site into homogeneous sections. It allows for allocation of a greater number of samples in strata with a higher variability in SOC stocks. For grid sampling, the site is divided into small areas or blocks. A sample location within each block is sampled several times. In general, the smaller the sampling unit, the greater the accuracy. Grid sampling is a practical and efficient technique and generally results in a better estimation of the variable of interest.

[2] Unlike single sampling, composite sampling combines a number of discrete samples collected from a body of material into a single homogenised sample for the purpose of analysis

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