



Food and Agriculture
Organization of the
United Nations



UNLOCKING THE POTENTIAL OF SOIL ORGANIC CARBON

OUTCOME DOCUMENT

GLOBAL SYMPOSIUM ON SOIL ORGANIC CARBON | 21 - 23 MARCH 2017 | FAO - ROME, ITALY



GLOBAL SOIL
PARTNERSHIP

ipcc

INTERGOVERNMENTAL PANEL ON
climate change



itps

INTERGOVERNMENTAL
TECHNICAL PANEL ON SOILS

UNCCD **SP** Science - Policy
Interface



United Nations
Convention to Combat
Desertification



World
Meteorological
Organization



UNLOCKING THE POTENTIAL OF SOIL ORGANIC CARBON

OUTCOME DOCUMENT
OF THE GLOBAL SYMPOSIUM ON SOIL ORGANIC CARBON
21-23 MARCH 2017 | FAO HEADQUARTERS - ROME, ITALY

An event co-organized by:

FAO | Food and Agriculture Organization of the United Nations

GSP | Global Soil Partnership

IPCC | Intergovernmental Panel on Climate Change

ITPS | Intergovernmental Technical Panel on Soils

UNCCD | United Nations Convention to Combat Desertification

UNCCD-SPI | Science-Policy Interface of the UNCCD

WMO | World Meteorological Organization

DISCLAIMER AND COPYRIGHT

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the organizing institutions – the Food and Agriculture Organization of the United Nations (FAO), the Global Soil Partnership and its Intergovernmental Technical Panel on Soils, the Intergovernmental Panel on Climate Change (IPCC), the United Nations Convention to Combat Desertification and its Science-Policy Interface, and the World Meteorological Organization – concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by the organizing institutions in preference to others of a similar nature that are not mentioned. The content of the outcome document and any conclusions or recommendations that it contains DO NOT reflect the official policy or the views of the organizing institutions. The views expressed in the outcome document reflect a summary of discussions by participants, supported by scientific evidence where appropriate, and subsequent recommendations.

IPCC co-sponsorship does not imply IPCC endorsement or approval of this outcome document or any recommendations or conclusions contained herein. The papers presented at the symposium and this outcome document have not been subjected to IPCC review.

ISBN 978-92-5-109759-5

© FAO, 2017

FAO encourages the use, reproduction and dissemination of material in this information product. Except where otherwise indicated, material may be copied, downloaded and printed for private study, research and teaching purposes, or for use in non-commercial products or services, provided that appropriate acknowledgement of FAO as the source and copyright holder is given and that FAO's endorsement of users' views, products or services is not implied in any way.

All requests for translation and adaptation rights, and for resale and other commercial use rights should be made via www.fao.org/contact-us/licence-request or addressed to copyright@fao.org.

FAO information products are available on the FAO website www.fao.org/publications and can be purchased through publications-sales@fao.org.

CONTENTS

Acknowledgements	IV
Abbreviations	V
Meeting organization and administrative support	VI
Summary	VII
Recommendations	VIII
Theme 1: Measuring, mapping, monitoring and reporting soil organic carbon stocks and stock changes	VIII
Theme 2: Maintaining and/or increasing SOC stocks (Fostering SOC sequestration)	VIII
Theme 3: Managing SOC in: soils with high SOC - peatlands, permafrost, and black soils; grasslands and livestock production systems; and dryland soils.	IX
Why the Symposium?	1
Symposium themes, key questions, and discussion summary	3
Theme 1: Measuring, mapping, monitoring and reporting SOC stocks and stock changes	3
Theme 2: Maintaining and/or increasing SOC stocks (fostering SOC sequestration)	7
Theme 3: Managing SOC in specific soils	12
Sub-Theme 3.1: Soils with high SOC	13
Sub-Theme 3.2: Soils in grasslands and livestock production systems	13
Sub-Theme 3.3: Dryland soils	14
Conclusions and way forward	18
References	20

ACKNOWLEDGEMENTS

The Organizing Committee and the Scientific Committee express their sincere gratitude to a number of countries, institutions and individuals for their important contributions to the success of the symposium.

Sincere gratitude goes to the Swiss Confederation, the European Commission and the Ministry for Foreign Affairs of Iceland for their financial support for the symposium.



©FAO/Cristiano Minichiello

ABBREVIATIONS

COP	Conference of the Parties	SDG	Sustainable Development Goal
FAO	Food and Agriculture Organization of the United Nations	SOC	soil organic carbon
GHG	greenhouse gas	SOM	soil organic matter
GSOC17	Global Symposium on Soil Organic Carbon 2017	SPI	Science-Policy Interface
GSOCMap	Global Soil Organic Carbon Map	UN	United Nations
GSP	Global Soil Partnership	UNCCD	United Nations Convention to Combat Desertification
GtC	gigatonne(s) of carbon	UNFCCC	United Nations Framework Convention on Climate Change
IPCC	Intergovernmental Panel on Climate Change	VGSSM	Voluntary Guidelines for Sustainable Soil Management
ITPS	Intergovernmental Technical Panel on Soils	WMO	World Meteorological Organization
LDN	land degradation neutrality	WOCAT	World Overview of Conservation Approaches and Technologies
MRV	measurement, reporting and verification		



©FAO/Matteo Sala

MEETING ORGANIZATION AND ADMINISTRATIVE SUPPORT

This outcome document, “Unlocking the potential of soil organic carbon”, was prepared and reviewed by members of the Scientific Committee (see below) but does not necessarily represent the views of those bodies or their member states. This document is also based on and complemented by a book of proceedings, which presents extended abstracts of the various sessions.

The **Scientific Committee** consisted of the following individuals and their respective affiliations (in alphabetical order, by name):

Intergovernmental Technical Panel on Soils (ITPS)

Mr Ahmad S. Muhaimed
Mr Amanullah
Ms Botle Mapeshoane
Mr Brajendra
Mr Daniel John Pennock
Mr Fernando Garcia Préchac
Mr Gan Lin Zhang
Mr Gary Pierzynski
Mr Gunay Erpul
Ms Isaurinda Dos Santos Baptista Costa
Mr Juan Antonio Comerma
Mr Kazuyuki Yagi
Mr Bhanooduth Lalljee
Mr Luca Montanarella
Ms Maria de Lourdes Mendonça Santos
Mr Martin Yemefack
Mr Miguel Taboada
Mr Neil McKenzie
Mr Nsalambi V. Nkongolo
Mr Pavel Krasilnikov
Mr Peter De Ruiter
Mr Rainer Horn
Mr Saéab AbdelHaleem Khresat
Mr Siosua Halavatau
Mr Talal Darwish
Ms Liesl Wiese (FAO/GSP Secretariat)
Ms Viridiana Alcantara (FAO/GSP Secretariat)
Mr Ronald Vargas (FAO/GSP Secretariat)

Intergovernmental Panel on Climate Change (IPCC)

Mr Andy Reisinger
(Vice-Chair, Working Group III, IPCC)

Science-Policy Interface of the UNCCD (UNCCD-SPI)

Ms Annette Cowie
Mr Axel Hebel (UNCCD Secretariat)
Mr Barron Orr
Mr German Kust
Mr Hamid Custovic
Mr Jean-Luc Chotte
Mr Joris de Vente
Ms Karma Dorji
Mr Martial Bernoux
Mr Victor Castillo (UNCCD Secretariat)

World Meteorological Organization (WMO)

Mr Robert Stefanski

Local Organizing Committee (FAO/GSP Secretariat)

Ms Clara Lefevre
Ms Daniela Colmenares
Mr Eduardo Mansur
Ms Fatma Rekik
Ms Giulia Stanco
Ms Maria Giuseppina Emiliano
Ms Isabelle Verbeke
Mr James Morgan
Ms Lucrezia Caon
Mr Matteo Sala
Ms Maryse Finka
Mr Rainer Baritz
Mr Sergio Zelaya
Mr Yusuf Yigini

SUMMARY

The Global Symposium on Soil Organic Carbon (GSOC17) was jointly organized by the:

- Food and Agriculture Organization of the United Nations (FAO);
- Global Soil Partnership (GSP) and its Intergovernmental Technical Panel on Soils (ITPS);
- Intergovernmental Panel on Climate Change (IPCC);
- Science-Policy Interface (SPI) of the United Nations Convention to Combat Desertification (UNCCD); and
- World Meteorological Organization (WMO).

The symposium was held at FAO headquarters in Rome, Italy, on 21–23 March 2017 and attended by 488 participants (33 percent women, 67 percent men) from 111 countries, including representatives of FAO member states, organizing institutions, the private sector and civil society, as well as scientists and practitioners working on soil organic carbon (SOC) and related fields.

The overall aim of the symposium was to review the role of soils and SOC in the context of climate change, sustainable development and land degradation neutrality (LDN). The three-day symposium was structured around three main themes focusing on the assessment of SOC, the maintenance and increase of SOC stocks, and SOC management in specific types of soil.

Participants from across the globe engaged actively by presenting the results of studies demonstrating the potential and challenges of managing and monitoring SOC and by discussing and developing the key messages reflected in this outcome document. The recommendations made based on this work are aimed at supporting the development of policies and actions to encourage the implementation of soil and land management strategies that foster the protection, sequestration, measurement, mapping, monitoring and reporting of SOC.



RECOMMENDATIONS



THEME 1: MEASURING, MAPPING, MONITORING AND REPORTING SOIL ORGANIC CARBON STOCKS AND STOCK CHANGES

Recommendation 1:

Organize capacity development and training for countries to develop national reference values for SOC stocks, as well as the necessary data management capacities and facilities.

This applies to all countries in need of such capacity, but priority should be given to countries using or needing the IPCC Tier 1 reference tables for SOC stock and stock change factors. Developing national reference values would enable countries to move to Tier 2 and to provide reference values that could be used for other national assessment and planning activities. In addition, such capacity development and training would support countries in moving towards SOC stock assessments for national SOC monitoring and reporting for the fulfilment of global conventions and mechanisms, as well as the ultimate goal of enabling local and national decisions on improving soil carbon management to sustainably enhance soil health and fertility and increase soil productivity. Such assessments for management decisions would entail more detailed assessments at finer scales, taking into account the complexity of SOC dynamics in relation to factors such as land use, soil type, climate and management practice.

Recommendation 2:

Establish a working group to develop feasible and regionally contextualized guidelines for measuring, mapping, monitoring and reporting on SOC that can be adapted locally to monitor SOC stocks and stock changes to support management decisions.

Such guidelines need to build on existing scientific guidance, such as that being refined by the IPCC, and they should be sufficiently simple to enable implementation in diverse contexts and scales and given differing local and national capacities and capabilities. Practical guidance should also include elements to support carbon-pricing mechanisms by relying on the measurement of SOC stocks to assess stock changes, rather than using only stock change factors based on land use and management practices. The working group should be established under the auspices of the GSP to facilitate collaboration among key scientific stakeholders, advisory panels and implementation bodies.



THEME 2: MAINTAINING AND/OR INCREASING SOC STOCKS (FOSTERING SOC SEQUESTRATION)

Recommendation 3:

In estimates of the potential for SOC sequestration, include the full GHG balance and consider possible interactions between the carbon and nitrogen cycles that could affect the climate change mitigation potential of applied practices.

There is strong potential to achieve SOC sequestration through land uses and land management practices, but estimates of the global potential for SOC sequestration vary in magnitude depending on which land-use categories, management practices, assumptions on SOC stock change, and GHG fluxes are used.

Recommendation 4:

The design of implementation strategies and appropriate soil and land management practices for SOC protection and sequestration should consider land use and the local environmental, socio-economic, cultural and institutional contexts, and potential barriers to adoption.

These considerations will determine the effectiveness of management practices and reduce uncertainties about the effects on SOC protection and sequestration. Numerous examples of practices that contribute to increasing SOC are available in various platforms, and combinations of practices are often most effective.

Recommendation 5:

Identify and specify the tangible short-term and long-term benefits for farmers of management practices for SOC sequestration to trigger their adoption, and introduce mechanisms to incentivize the adoption of such practices.

Benefits may include yield increases, drought resistance, economic benefits and other incentives. Incentive mechanisms could include payment schemes for ecosystem services, such as carbon credits programmes, the establishment of sustainable business models, linking existing agricultural subsidy schemes to sustainable practices, capacity development, and implementation support. Information on benefits should inform the development of local solutions and context-specific policies to support the implementation of such practices at the local level, as well as to enable efficient training and communication on the overall benefits of SOC-sequestering management practices. Incentives are needed in addition to existing convincing scientific evidence that sustained increases in SOC contribute to achieving objectives related to climate change mitigation and adaptation, food security and LDN.



THEME 3: MANAGING SOC IN SOILS WITH HIGH SOC (PEATLANDS, PERMAFROST AND BLACK SOILS); GRASSLANDS AND LIVESTOCK PRODUCTION SYSTEMS; AND DRYLAND SOILS.

Recommendation 6:

Prevent SOC losses by maintaining current SOC stocks (especially in carbon-rich soils) as the minimum action on SOC management.

Achieving this goal would contribute to climate change mitigation by reducing carbon inputs to the atmosphere and to LDN and food security by preserving existing SOC for soil health and associated benefits, including reducing the risk of further soil degradation.

Recommendation 7:

Prioritize soils with the highest carbon stocks in the development of national and regional policies on soil conservation to prevent SOC losses.

Such soils include peatlands, permafrost areas and numerous high-SOC soils, such as black soils. In peatlands, priority should be given to the vast areas of unmanaged and pristine peatlands, especially in regions where peatlands are vulnerable to land-use change due to their high production potential.

Recommendation 8:

Support land-users sufficiently to implement and sustain appropriate soil and land management practices to protect and enhance SOC under local conditions for long-term benefit.

This includes refining the Voluntary Guidelines for Sustainable Soil Management to provide guidelines on the sustainable management of SOC at the national and local scales to encompass site-specific conditions.



WHY THE SYMPOSIUM?

Soils have become one of the world's most vulnerable resources in the face of climate change, land degradation, biodiversity loss and increased demand for food production.¹ Notwithstanding the enormous scientific progress made, the protection and monitoring of soil resources at the national to global levels face complex challenges restricting the design and implementation of on-the-ground policies. There is insufficient global support for meeting these challenges, which vary widely by region, and therefore for the protection and sustainable management of the world's soil resources.

Soil organic matter (SOM) is a key element of soil health because it regulates many soil functions, including carbon storage as soil organic carbon (SOC); the storage, availability and cycling of plant nutrients; soil biodiversity; soil porosity, aeration, water-holding capacity and hydraulic conductivity; thermal properties; and mechanical strength. The link between SOM and soil fertility has been known for more than a century.² The role of soils and SOC in the climate system and in the context of climate change adaptation and mitigation has become recognized only in recent decades, but it has been validated in various studies, both experimentally and through modelling.³ Managing SOM is one of the key strategies for achieving land degradation neutrality (LDN). The conservation and monitoring of SOC stocks at the national to global levels is a complex challenge requiring locally adapted policies to ensure the effective implementation of relevant practices.

Soils constitute the largest terrestrial carbon pool⁴ and play crucial roles in the global carbon balance by regulating dynamic biogeochemical processes and the exchange of greenhouse gases (GHGs) with the atmosphere.⁵ The top 1 m of soil contains an estimated 1417 gigatonnes (GtC) of SOC,⁵ which is nearly twice the quantity of atmospheric carbon (847 GtC as carbon dioxide – CO₂). Land-use and land-cover change is the second-largest anthropogenic source of atmospheric carbon.⁶ SOC stocks in the upper soil layers (750 GtC in 0–30 cm) are especially sensitive and responsive to changes in land use and management. This presents an opportunity to influence the amount of CO₂ in the atmosphere by maintaining existing soil carbon stocks (preventing carbon losses, which is particularly important in soils with high SOC content) and by storing additional carbon in soils through SOC sequestration. The potential for SOC storage varies with local conditions and sometimes involves trade-offs with other land management objectives. Importantly, SOC storage should not result in increased emissions of other GHGs, especially nitrous oxide (N₂O), a potent GHG.

SOC can exist in soils in a variety of pools, ranging from freshly deposited plant residues to organic carbon contained in complex, stable molecular structures such as those found in compost, biochar and SOM adsorbed onto clay particles and bound in soil aggregates. The residence time of SOC in the soil system can range from days to thousands of years. The scientific literature strongly supports the multiple benefits of adding organic carbon to soils for climate change mitigation and adaptation, food security and achieving LDN. Efforts to increase SOC, therefore, are often viewed as “no regrets” actions, but the potential to achieve each benefit depends on local environmental, socio-economic and cultural conditions. Carbon sequestration occurs when a trend of increasing SOC stocks over time is discernible despite short-term fluctuations. Climate change mitigation occurs when SOC stocks increase over time and there is a net reduction in GHG emissions when considering all GHG sources and sinks affected by SOM management (CO₂, methane – CH₄ – and N₂O). Climate change mitigation is also achieved when SOC losses are prevented, thus avoiding additional GHG emissions.

The role of soils and SOC in the climate system and climate change adaptation and mitigation has been recognized widely and validated in various studies, both experimentally and through modelling.^{3,7} Large-scale baseline and trend assessments are still inaccurate, however, and many of the factors determining SOC quality and quantity in different regions – as affected by climate change and measures to enhance SOC – are insufficiently investigated.⁷ FAO, the GSP and its ITPS, the IPCC, the UNCCD and its SPI, and the WMO agreed to co-sponsor GSOC17 in light of the important contributions that maintaining and enhancing SOC can make to meeting the objectives of LDN, reducing GHG emissions, and enhancing climate change adaptation.

The **overall aim** of the symposium was to review the role of soils and SOC in the context of climate change, sustainable development and LDN. The symposium also aimed to build scientific evidence that could be assessed in regular IPCC assessment reports, starting with the Sixth Assessment Report and other reports to be produced in the sixth assessment cycle, as well as reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and the UNCCD and on the Sustainable Development Goals (SDGs).

Specifically, the aim was that symposium outcomes would provide crucial information that could contribute to the:

- refinement of methodologies for reporting on SOC, as outlined in Volume 4 (Agriculture, Forestry and other Land Use) of the Outline of the Methodology Report(s) to refine the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, which was adopted in Decision IPCC-XLIV/L.3 at the 44th Session of the IPCC;
- Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security and Greenhouse Gas Fluxes in Terrestrial Ecosystems, which was agreed at the 43rd Session of the IPCC; and
- LDN Target Setting Programme implemented by the UNCCD.

The specific objectives of the symposium were to:

- 1) examine current scientific and technical understanding of the role of soils and SOC in the climate system for carbon sequestration and climate adaptation;
- 2) review the potential and limitations of SOC management to contribute to climate change mitigation and adaptation, addressing land degradation, and meeting the SDGs;
- 3) review current knowledge on the impacts of land and soil management on SOC (and SOC stabilization and destabilization mechanisms), including the identification of practices that increase SOC;
- 4) enable and strengthen the provision of knowledge on SOC measurement, modelling and management and the interlinkages with land degradation and climate change to inform upcoming IPCC assessment reports and reports to initiatives addressing land degradation;
- 5) identify knowledge gaps and explore opportunities for collaborative research; and
- 6) identify policy options for relevant soil and SOC priorities to encourage the adoption of practices that optimize SOC sequestration and stabilization in national climate change agendas.

SYMPOSIUM THEMES, KEY QUESTIONS, AND DISCUSSION SUMMARY

The symposium's three main themes were designed to focus discussions on the assessment of SOC, the maintenance or increase of SOC stocks, and SOC management in specific soil types. In the lead-up to the symposium, key questions were developed for each theme to stimulate discussion and help in identifying priority actions. Scientific presentations in parallel sessions set the scene for debating the thematic questions, and working-group discussions were held on the morning of the last day to develop answers to those questions. Due to the nature of the questions, concrete answers were not always possible based on discussion alone. As a result, discussions mostly focused on the ultimate goals implied in each question and what needs to be considered in developing appropriate answers.

The GSOC17's themes and subthemes (where applicable) are listed below, with brief contextual summaries of their importance. This is followed by a summary of the main discussion points on each question, as agreed by consensus by participants during the working-group sessions.



THEME 1: MEASURING, MAPPING, MONITORING AND REPORTING SOC STOCKS AND STOCK CHANGES

The national monitoring of, and reporting on, SOC is becoming increasingly important in the fulfilment of global conventions and mechanisms. Under the UNFCCC, for example, national SOC stock changes are assessed annually in Annex 1 countries in relation to GHG emissions. Under SDG Target 15.3,* SOC is assessed as one of three subindicators (land cover [metric: land-cover change]; land productivity [metric: net primary productivity]; and carbon stocks above and below ground [metric: SOC]) of Indicator 15.3.1 ("Proportion of land that is degraded over total land area"), in accordance with the UNCCD's LDN concept.⁹

SOC stock changes are assessed based on the following guidelines:

- For UNFCCC reporting, SOC stock changes are assessed using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.¹⁰ Updated guidelines will be released by 2019¹¹ to provide a sound scientific basis for future international climate action, especially under the Paris Agreement¹² (which will come into effect in 2020).
- For reporting on SDG 15.3.1, metadata,¹³ as well as the Framework and Guiding Principles¹⁴, broadly outline the method for computation of subindicators. The Framework and Guiding Principles emphasizes the need to standardize and harmonize SOC data, as well as for the compilation of new data in a central database to improve data availability for future mapping activities. In terms of modelling SOC stock changes, the Framework refers to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
- Guidance for the measurement of SOC as one of the metrics of LDN is under development and will be based on the measurement of SOC stock change averaged over 10–15 years, starting from a baseline. Such measurements are likely to be derived from a combination of remote sensing data and ground measurement.⁹

Despite the existence and further development of methods for measuring and assessing SOC stocks and stock changes within the frameworks of GHG emissions and land degradation, reporting on the status and trends of SOC based on measurements remains a challenging task.¹⁵ Given that SOC stock change is an indirect indicator of land and soil degradation, several associated challenges also need to be addressed. These include the limited availability of datasets on SOC stocks at the national and regional levels; the lack of harmonization of SOC measurement methods and subsequent SOC data and information; the uncertainties associated with existing data for monitoring SOC stock changes, taking into account the large spatial and temporal variability of soil carbon stocks; and wide variability in the impact of management practices on SOC stocks, which limits

* SDG Target 15.3: "By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world".

the capacity to model SOC stock change. The lack of regular monitoring of country-level SOC stocks often leads nations to report that no SOC stock changes have occurred, which could cause large biases of unknown direction in global and national GHG emissions accounting.

A further point for consideration in the context of SOC monitoring is measurement, reporting and verification (MRV), which is aimed at tracking countries' progress in climate change mitigation¹⁶ and involves tracking all measures taken by countries to collect and report data on emissions, mitigation actions and support. MRV related to SOC focuses on GHG emissions or SOC change rather than on SOC stocks *per se*. This begs the question of whether specific MRV guidelines are necessary for assessing both SOC stocks and SOC stock change, not only in relation to GHG emissions and climate change but also in the context of land degradation-related reporting and decision-making on soil and land management practices.

Discussion Summary

Participants remarked that, although the background to the theme highlighted the importance of national SOC monitoring and reporting for the fulfilment of global conventions and mechanisms, the **ultimate goal in assessing SOC stocks and stock change** is to develop mapping and inventory products that **enable local and national decisions that improve soil carbon management** towards improving soil health and fertility and increasing soil productivity. To achieve this goal, more detailed assessments are needed at finer scales, taking into consideration the complexity of SOC dynamics in relation to, for example, soil type, climate regime, land use and management.

Q1-1 What are the latest and reliable reference values for SOC stocks, and stock change factors based on country- or region-specific data for the most important land uses to be updated in the 2006 IPCC Guidelines?

This question was not answered directly by supplying reference values for SOC stocks and stock change factors. Rather, the need for and development of such reference values was discussed.

Current reference values for IPCC Tier 1 SOC stocks (Table 2.3 in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories¹⁰ and subsequent updates) are crude, and they are restricted to a limited group of soil types and climatic regions. Nonetheless, many countries lacking national reference values still use these values. Batjes (2011) developed updated reference values for the default IPCC climate–soil clusters,¹⁷ which showed that mean SOC stocks to the IPCC reference depth of 30 cm varied greatly within each cluster. Reducing uncertainties within these clusters would require finer criteria for defining climate zones and soil classes and the replacement of default reference stocks and stock change factors with region-specific values.

Although Tier 1 reference values are used, it was **recommended that countries be incentivized to develop national reference SOC stock values**. Once developed and published, such values could be used to support the periodic updating of the 2006 IPCC reference values, in addition to other applications. By developing national reference SOC stock values, countries would move to Tier 2 and could use the 2006 IPCC reference table as a transition step in this process. Further emphasis under Tier 2 would be to develop national values for stock change factors with reference to the 2006 IPCC land-use matrix. Many countries will need **capacity development and training** to support such activities, as well as adequate data management capacities and facilities.

Should specific MRV guidelines be developed to track SOC stocks and stock changes and if yes, what are the main methodological considerations?

The answer of participants to the first part of this question was “yes”: specific **MRV guidelines should be developed to properly address and monitor SOC stocks and stock changes** from the local (project) level to the national level. Such guidelines would build on existing scientific guidance, such as that being refined by the IPCC. To support the assessment of SOC at the project level, MRV guidelines need to be simple and sound. They also need to include sufficient elements to support carbon-pricing mechanisms that rely on the measurement of SOC stocks for assessing stock changes, or models validated through local measurement, rather than stock change factors based on land use and management practices. Activity-based methodologies are preferable due to their lower transaction costs and skill requirements, as well as easier verification.

Market-based mechanisms penalize uncertainty, especially related to the permanency of SOC sequestration and rates of change in SOC stocks. Hence, estimates need to be as precise as possible while considering the inverse relationship between precision and cost. Estimates need to be as accurate as is justified by the relevant carbon price, and a mechanism should be included to incentivize countries to optimize precision in SOC measurement and assessment. In addition, methodological aspects need to ensure that changes (gains and losses) in SOC stocks are detected when they occur. This will necessitate guidance on the sampling density required at monitoring sites, as well as realistic time intervals for sampling and assessment.

Appropriate standards need to be defined to enable all this, and countries should have sufficient opportunity to provide inputs into the development of such standards and methods, as well as scope for adjusting assessments to national priorities. A tiered approach would be essential for providing simpler and more accessible methods for countries with less expertise, data and information.

Many countries are implementing SOC mapping as part of the Global Soil Organic Carbon Map (GSOCMap) activity of the GSP to develop national SOC stock maps, and this could be expanded to include the analysis of new soil samples according to accepted and harmonized methods. Such harmonized methods would include consideration of:

- using equivalent soil mass rather than bulk density or equivalent soil volume to calculate SOC stocks;
- using proximal sensing techniques to measure SOC, both in the laboratory and in situ, ensuring sufficient calibration of such techniques at the local, national and regional levels; and
- sampling to appropriate soil depths to measure changes in SOC stocks as a function of soil and land management practices.

The comparability of SOC stocks between countries is important and should be considered in a bottom-up approach to enable scaling up from the national to the global level and to improve comparability between bottom-up and top-down approaches. It is recommended, therefore, that MRV guidelines include guidance on how comparability (between countries and between bottom-up and top-down) can be achieved.

Q1-3

How can the uncertainties of SOC stock and stock change estimates be reduced?

Participants agreed that, to reduce uncertainties in estimates of SOC stock and SOC stock change, they need to be sufficiently quantified.

Uncertainties are cumulative from the time of soil sampling, analysis and data transformation through to map development; uncertainty assessment and reduction, therefore, is needed at all these stages. Guidance on uncertainty assessment is necessary for both existing and new data, and it should address the issue of harmonizing soil sampling and analysis for SOC measurement. Guidance is also needed on how to organize data and transform them into relevant products.

Effective sampling, correcting for soil depth, and considering the equivalent soil mass for SOC stock calculation can reduce uncertainties associated with SOC measurement. Sufficient laboratory ring tests (involving collaborative laboratory comparisons using common samples) would increase quality assurance for soil analyses and thereby reduce uncertainties associated with SOC measurement. There should be sufficient regional and international soil laboratory networks to support ring tests and to provide soil analysis facilities for countries that lack their own. However, the development of laboratory networks should not replace the establishment of national facilities or the building of national capacities. The symposium heard that many countries are determined to build their national capacities in soil analysis and SOC assessments.

Taking soil samples where no data are available, or increasing the number of samples in existing assessment areas, can further reduce uncertainty. This might require large investments in soil sampling and analysis, however, so methods for cheaper and faster analyses are important, such as those used in proximal sensing. The potential reduction in accuracy associated with, for example, infrared spectroscopy could be offset by a large increase in the number of samples analysed and the quantity of data generated.

Uncertainties associated with land uses and land management practices should be determined and taken into consideration in SOC assessments, and protocols for quality control and quality assurance need improvement.

Q1-4

What are the recent developments in reliable methods and models to quantify stock changes and how can these be best applied for SOC measurement and monitoring?

Before discussing the methods and models available for quantifying SOC stock changes, it was clarified that the measurement and monitoring of SOC would be necessary at various spatial scales, from local (project) to national and global, to enable predictions for different end-user needs. Countries are the end users of products aimed at policy development. Hence, policy-relevant monitoring products should be developed at policy-relevant scales, and countries should be supported to develop the necessary SOC products.

A multitude of SOC-related models exists that operate under varying assumptions and input data. Multi-model approaches could be implemented in which each model is applied for its intended purpose and strengths and to reduce model errors and product uncertainties. Modelling should be at sufficiently high resolution to adequately inform management decisions and drive change.

The effects of soil erosion on SOC sources and sinks should be included in SOC modelling, and the measurement of gravel and stone content should be improved to remove biases in estimates of SOC stocks. Various (short-term) indicators of SOC stocks and stock changes could be investigated to enable the early detection of stock change. The use of isotope technology may be useful in determining such short-term indicators.

The informed use of data-driven methods versus process-based methods is important, especially in terms of modelling SOC in areas such as peatlands. For data-driven soil modelling approaches, which rely on soil profile datasets, some peatland maps can suffer from problems associated with spatial scale (e.g. the predominance of small peatlands in the large soil units modelled). However, data-driven methods that do not consider landscape processes are generally missing variables that are necessary to properly model the occurrence of peat.



THEME 2: MAINTAINING AND/OR INCREASING SOC STOCKS (FOSTERING SOC SEQUESTRATION)

SOM comprises a complex mixture of partially decomposed organic substances derived from plant litter, as well as faunal and microbial biomass.¹⁹ SOM plays a crucial role in many soil functions and ecosystem services, such as buffering against climate change, supporting food production and regulating water availability. Changes in the quality or quantity of SOM affect the capacity of soils to perform these ecosystem services and SOM, therefore, needs careful management. SOM is composed of roughly 58 percent carbon,²⁰ which equates to SOC. SOM stocks are influenced by microbial activity, the accessibility of organic residues to microbes, soil textural and structural types, site conditions, and management practices. Managing SOC through sustainable agricultural and other land-use practices has become a widely acknowledged strategy for restoring healthy soil properties and thereby combating land degradation and desertification and enhancing the resilience of agro-ecosystems to environmental shocks, although it is a long-term process.²¹

Maintaining and increasing SOC stocks is not only crucial for reducing GHG emissions and removing CO₂ from the atmosphere but also for harnessing the benefits of increased SOC (and SOM) for soil health and fertility by improving water storage and thereby increasing the access of plants to water, food production potential and resilience to drought. SOC is also a key indicator for LDN because it is a proxy for change in land condition. Even though soils host the largest terrestrial carbon pool, soil degradation, land use and land-use change have resulted in losses of 25–75 percent of the original SOC stocks. Further SOC losses need to be prevented, especially in high-carbon soils, and SOC stocks need to be at least partially restored through carbon sequestration.

SOC is very heterogeneous, with residence times ranging from hours to millennia. Most models of SOM divide SOC into kinetic pools with different residence times (e.g. fast-active, slow-intermediate and very slow/passive/inert). The turnover rate of each pool depends on diverse processes and factors, such as the accessibility of organic matter to decomposers, the involvement of organic compounds in organo-mineral interactions, the recalcitrance of organic matter, and environmental conditions (e.g. climate and pH).²² In considering the effect of land management practices on SOC levels, therefore, the study of SOC stabilization (e.g. interactions between SOM, soil microbes and soil minerals affecting the protection of SOM through aggregation and sorption²³ and thus affecting relative residence time) and mineralization (e.g. soil disturbance and loss of protection) mechanisms and the improved accessibility of pores and particle surfaces in well-structured aggregates are essential for determining the true effect on GHG emissions and SOC sequestration.²⁴

Discussion Summary

Land uses and land management practices that maintain or increase SOC stocks have multiple benefits for climate change mitigation and adaptation, food security, LDN and biodiversity. Participants found there are many strategies for increasing soil carbon but that **responses vary** by climate and soil type, so **practices should be selected to suit each context**. The following widely applicable recommendations for maintaining or increasing SOC were identified: control soil erosion; maintain ground cover; apply integrated nutrient management; encourage diversified farming systems; incentivize and empower farmers to manage SOC; and encourage collaboration between scientists, farmers and policy-makers to devise strategies for increasing SOC.

Q2-1 What is the global potential for achieving SOC sequestration across land uses, and what is uncertainty associated with achieving this?

Through the adoption of recommended management practices, an estimated 1–2 GtC per year could be sequestered globally within 30–50 years.²⁵ This assumes that 70 percent of managed ecosystems (including croplands, grazing lands, forests and woodlands) implement management practices that foster SOC sequestration, 50 percent of degraded soils are restored, and soil inorganic carbon sequestration occurs on all dryland soils. The main carbon sequestration potential is in degraded soils, where SOM has largely been depleted. On the other hand, soils with high SOC content will possibly not sequester further significant amounts of carbon if they are already close to local SOC saturation. In such soils, preventing SOC losses should be the priority. Sommer and Bossio (2014)²⁶ pointed out that the rate of SOC sequestration declines over time, reaching maximum sequestration after 20–40 years. They calculated the cumulative global potential for carbon sequestration in arable land, permanent meadows and pastures at between 32 GtC and 63 GtC (for pessimistic and optimistic scenarios, respectively) between 2014 and 2100.

Notwithstanding the strong potential for SOC sequestration and the associated contribution to climate change adaptation and LDN objectives, it is crucial to **assess the full GHG balance** from a life-cycle perspective (e.g. emissions associated with land use across the supply chain, including aspects such as fertilizer manufacture and use), taking into account interactions between the carbon and nitrogen cycles as well as emissions arising from specific land uses that may affect the potential to mitigate climate change. The effectiveness of measures aimed at maintaining or increasing SOC stocks is determined by existing land uses and farming practices; local environmental (e.g. soil, climate and microbial communities), socio-economic, cultural and institutional contexts; and local farming systems. Depending on the combination of these factors, **the achievable local or regional SOC sequestration may be lower than the theoretical SOC sequestration potential.**

Q2-2 What are the upper limits (potential saturation levels) to SOC sequestration potential?

Saturation levels for SOC sequestration were not defined at the symposium. Participants agreed, however, that when soils are managed as carbon sinks, SOC will increase up to the point at which a new SOC equilibrium is reached. This equilibrium represents the balance between organic matter inputs and SOM turnover.²⁶

The upper limit or saturation of SOC refers to the upper limit of the soil's capacity to protect organic matter from mineralization and depends on site-specific soil and environmental conditions, including vegetation type and soil physical, chemical and biological properties (e.g. clay content, clay type, and the accessibility of particle surfaces to microorganisms). The aim of managing SOC for sequestration purposes, therefore, is to achieve a new equilibrium as close as possible to saturation and to maintain that level once reached. This includes the potential for SOC storage in subsoils, which are often below saturation levels.

Because SOC sequestration is a slow and management-intensive process, the upper limits of SOC sequestration potential are most relevant in soils with relatively high SOC contents, approaching the saturation value, and less important in SOC-depleted systems. Dryland areas have less potential for SOC sequestration than humid areas because of the limited availability of water, but even small SOC gains in drylands could have a crucial impact on food security, climate adaptation and LDN by improving soil health. The application of biochar could add additional carbon to soils that is not limited by intrinsic SOC storage capacity.

Q2-3 What is the long-term stability of SOC and its components and what is the long-term sustainability of SOC sequestration?

The long-term stability and sustainability of SOC sequestration depend on sustaining best management practices and ensuring that carbon inputs are larger than carbon losses by mineralization. This highlights the need to foster acceptance and the wider-scale adoption of SOC sequestration practices through participatory processes, building on local knowledge, incentivizing farmers, empowering extension services and increasing communication among stakeholders.

Not all SOC is equal. The protection and stability of SOC is determined ultimately by a combination of the quantity, quality and dynamics of SOM, as well as by environmental and pedo-climatic conditions, the soil's physicochemical properties, biological processes, microbial communities, the quality of organic inputs, and the level of SOC protection through organo-mineral interactions and the formation of stable soil aggregates. Chemically and physically stable fractions of SOC, stabilized through intrinsic recalcitrance or association with minerals, need to be preserved, therefore, to ensure the long-term sustainability of SOC sequestration. The maintenance of soil functions and soil structure should be a target for both improving soil health and fertility and maintaining and increasing SOC.

Climate variability, climate change and water management additionally affect SOC stability because temperature and soil moisture affect SOC mineralization rates. Increases in temperature lead to the increased loss of SOC due to mineralization, with a larger effect in cold climates than in warm climates and in soils with large SOC stocks than in carbon-poor soils. Knowledge gaps exist on the effects of climate change on SOC stocks and fluxes, such as the impact of increased CO₂ concentrations on crop yields and carbon inputs.

The specific impact of soil erosion on SOC stability depends on the transformation processes that occur during soil transport and deposition, the location of deposition (deep burial and depositions in aquatic environments increase stability) and the extent to which the dynamic replacement of SOC (replacing eroded SOC with newly produced SOC) occurs at eroding sites. Regardless of these factors, however, reducing or preventing soil erosion will help protect SOC in soil aggregates and prevent SOC losses at any specific site.

Land-use change is an important possible cause of SOC losses and gains, depending on the initial and final land use. SOC is easily and rapidly lost in some land-use changes (such as conversion from grasslands to croplands), but the restoration of SOC stocks is slow ("fast out, slow in") when converting croplands to grasslands or forests, for example. It is essential, therefore, to prevent SOC losses in both carbon-rich and carbon-poor soils to minimize the future need for SOC sequestration.

Q2-4 Is there sufficient scientific evidence to establish whether SOC sequestration contributes to climate change adaptation, mitigation and achieving LDN?

There is convincing scientific evidence that a **sustained increase in SOC contributes to the multiple objectives of climate change mitigation and adaptation, food security and achieving LDN**. The Voluntary Guidelines for Sustainable Soil Management (VGSSM) and the World Overview of Conservation Approaches and Technologies (WOCAT) provide useful recommendations and examples of local sustainable management practices that contribute to SOC sequestration. Examples of practices that directly or indirectly support the maintenance or increase of SOC and which can be designed according to local conditions include conservation agriculture; crop rotation; the application of biochar; cover crops; catch crops/green manure; agroforestry; compost application; organic amendments; integrated nutrient management; grazing management; forest management; and water harvesting. The combined implementation of practices that address both soil and water conservation, the diversification of cropping systems, the integration of crop and livestock systems, and agroforestry are most effective for SOC sequestration and should be prioritized.

Practices to foster SOC sequestration focus either on actively increasing organic material inputs or on slowing organic matter turnover rates by reducing disturbance (e.g. through no-tillage). Measures that increase the input of organic materials (e.g. cover crops, rotations, stubble retention, improved grazing management, and agroforestry) are more effective in sequestering SOC than those that only reduce disturbance by tillage or erosion.

There is ample evidence that increasing SOC has positive impacts on soil health and resilience to climate change and drought by increasing water-holding capacity, drought resistance and erosion and flood control. There are often synergies between climate change adaptation and mitigation and achieving LDN in relation to SOC management. Therefore, even in cases where mitigation objectives are not fully achieved due to the effects of other GHG fluxes or slow increases in SOC (e.g. using reduced tillage), maintaining or increasing SOC still has vital soil health benefits that support food security, climate change adaptation and achieving LDN.

The following guiding principles and constraints were identified to optimize the benefits of SOC sequestration for climate change mitigation and adaptation and LDN and should be considered in the design and implementation of soil and land management practices:

- Practices to foster SOC sequestration must be tailor-made because the effectiveness of measures depends on existing land uses and farming practices, the types of measures taken, and the environmental, economic, institutional and social conditions.
- Increasing SOC alone is insufficient to enhance soil health. The biological response to warming, enhanced carbon inputs, and changing precipitation regimes also need to be considered to ensure the greatest effectiveness in climate change adaptation and LDN.
- Some of the uncertainty in understanding the responses of SOC to management practices arises from the inherent variation in driving variables, such as the properties of soil and organic inputs and the climatic regime. However, much of the uncertainty and apparent temporal and spatial variability in the effectiveness of practices can be explained by experimental design factors, such as differences in the duration of experiments and sampling depth, and the scope of assessment (e.g. SOC only, or also litter and biomass pools; carbon only, or all GHGs; on-farm only, or full life cycles). Long-term monitoring and sampling deeper than the near-surface soil horizons is recommended to reduce uncertainties due to experimental design factors. The assumed response of SOC to climate change adds further uncertainty. Interactions between carbon and nitrogen cycling and trade-offs between different GHG emissions should also be considered in understanding the impacts of management on SOC.
- Under certain conditions, best management practices may result in an avoided loss of SOC compared with business-as-usual practice but not in a net increase in SOC stock. This still represents a benefit for climate change mitigation by reducing CO₂ emissions and contributes to climate change adaptation and LDN by preventing soil degradation through the loss of SOC.
- The potential to increase organic material inputs is often limited by competition for resources. In some contexts, no additional organic material may be available for use as amendments because it is being used for animal feed, fuel or other purposes.

How can policies support the adoption of practices that foster SOC sequestration and how can scientific evidence be packaged to inform such policies?

Increasing the implementation of soil and land management practices that protect or increase SOC is an important social challenge. To trigger the wide-scale adoption of sustainable practices, **tangible short- and long-term benefits for farmers**, such as yield increases or stabilization and resistance to drought, must be evident, highlighted and achievable. The multiple benefits of SOC sequestration for human well-being include the protection of ecosystem services and functions (comprising provisioning, regulating, supporting and cultural services), as well as the conservation and restoration of biodiversity. Farmers are most likely to contribute to increasing carbon sequestration if they are convinced it enhances production and food security, or if there are economic benefits or other direct incentives. Therefore, evaluations and feasibility studies of alternative management practices should include socio-economic aspects and a complete value-chain analysis to inform land-user decisions on soil and land management options. The availability of such information does not guarantee that land users will change their management practices, however, because of barriers to the adoption of SOC sequestration enhancing practices, such as the following:²⁷

- Financial barriers – such as limited finance and access to capital – may discourage farmers from implementing SOC-building practices.
- Technical and logistical barriers may include the unavailability of appropriate technologies, technical capacity or equipment and the low detectability of short-term changes in SOC stocks.
- Institutional barriers may take the form of national policies and regulations, insecure land tenure, imperfect markets, limited research and extension services, and weak interinstitutional coordination.
- Knowledge barriers may include a lack of information on weather conditions or of management options and their proper implementation. In some cases, it is not so much about the transmission of knowledge to farmers but who is transmitting it. Information from politically affiliated sources, for example, may be regarded with scepticism, and information from apolitical sources is preferred.
- Resource barriers relate to the absence of sufficient land, labour, inputs, water or plants to implement climate adaptation and mitigation practices.
- Socio-cultural barriers can be cognitive or normative. The way in which farmers perceive climate change and the identification of risks is one of the key barriers influencing people's actions in dealing with climate change mitigation and adaptation.

Mechanisms are needed, therefore, to **facilitate and incentivize the implementation of management practices** that contribute to SOC sequestration and remove the barriers to adoption of such practices. Such mechanisms include:

- a. Developing payment schemes for ecosystem services to compensate farmers and land managers for the possible additional costs of implementing alternative management practices that help protect ecosystem services for society as a whole (e.g. carbon credit programmes).
- b. Identifying and establishing sustainable business models and investment opportunities in landscape restoration, regenerative agriculture and sustainable land management. Assessments of the cost of no action may also be required.
- c. Establishing long-term financial commitments and agreements for governments.
- d. Operationalizing SOC management, maintenance and sequestration at the local and national levels through synergies among the three relevant UN conventions (i.e. the Convention on Biological Diversity, the UNCCD and the UNFCCC) and the SDGs.
- e. Developing policies that ensure the effective and consistent communication of information on relevant management practices and their implementation, and strengthening policies that support those stakeholders providing information on SOC sequestration practice arising from research, analytic systems, extension services, industry and regional networks.

- f. Acknowledging local context, such as belief and value systems and indigenous knowledge and practices, in the design and implementation of relevant management practices.
- g. Making available existing technologies for implementing relevant practices and investing in new technical and management strategies, such as improved varieties.
- h. Developing new infrastructure (e.g. efficient water-use technologies and transport and storage systems) and establishing accessible and efficient markets for products.
- i. Increasing local training and support for the adoption of new management practices.
- j. Linking existing agricultural subsidy schemes to sustainable agricultural practices that support the maintenance and enhancement of SOC, water quality and biodiversity to promote the implementation of such practices.

Stakeholder participation, knowledge exchange, open source data, education, clear communication, and interdisciplinary research that considers all land uses (not only agriculture) are crucial for the adoption of alternative practices. All stakeholders, including the research community, practitioners, farmers, landowners and policy-makers, should engage in participatory processes to co-develop knowledge and learn from each other in a collaborative, interactive and iterative model, because there is a need to act while learning and to incorporate this learning in adaptive strategies. Well-designed participatory research and policy development often facilitate the design and use of tailor-made or existing **local solutions and context-specific policies** and increase their acceptance and adoption, as illustrated in many successful community initiatives to implement alternative management practices. On-farm assessments and participatory monitoring programmes can help increase awareness and the exchange of knowledge. Hybrid knowledge developed through participatory processes that combine scientific evidence and local knowledge should inform policies at different levels.

Policies should avoid adding obstacles to farming practices that might lead to negative feedbacks, and they should include clear recommendations and targets for SOC sequestration. The target should be achievable, and the practices should be clear and realistically implementable. Farmers should be given sufficient information to illustrate the benefit of healthy soils beyond climate change mitigation. This involves communicating the consequences of inaction and the opportunities for action.

There is **no one-size-fits-all scenario for training and communication** because evidence needs to be packaged differently for different stakeholders. Education, training and capacity building for policy-makers, farmers and extension services, and ensuring secure land tenure, are other crucial means for fostering the adoption of sustainable land management practices. Narratives of “good” and “bad” stories from people affected by soil degradation and those who have benefited from good SOC management can additionally raise awareness and encourage wide-scale adoption.



THEME 3: MANAGING SOC IN SPECIFIC SOILS

The distribution of SOC is very heterogeneous and a function of, among other things, soil type, land use, land-use change, climate, landscape, and soil management practices. As a result, soils in different geographic areas have differing potential as carbon sources and sinks and require different management practices to ensure carbon flows that sustain soil and ecosystem services. Three subthemes enabled discussions on the management of soils with differing SOC source or sink characteristics.

SUB-THEME 3.1: SOILS WITH HIGH SOC

In the context of climate change, maintaining existing levels of SOC is especially important in soils with inherently high SOC, such as peatlands, permafrost and black soils.[†] This is due mainly to their potential as sources of significant carbon emissions (especially CO₂ and CH₄), even though they cover proportionally little of the global land surface. Besides their high SOC content, many of these soils have inherently high productivity and fertility, are highly relevant to food security when cultivated, and are therefore often extensively farmed. Such soils are also highly significant as potential SOC sinks through improved management practices in areas where historical SOC losses have occurred. There is still significant uncertainty about the carbon stocks and flows in high-SOC soils, however, because their extent, status and dynamics have not been estimated or mapped with sufficient accuracy.

Peatlands, for example, cover roughly 3 percent of the global land surface.²⁸ According to the Global Peatland Database, peatlands contain a total SOC mass of 447 GtC for their total depth, but uncertainties around this estimate are high,²⁹ due largely to uncertainties on peatland depths.³⁰ In the case of permafrost soils, it is considered that about 30 percent of the total SOC stock to a depth of 2 m is held in the Northern Circumpolar Region, with estimated SOC stocks of 217 ± 12 GtC at 0–30 cm and 1 035 ± 150 GtC at 0–300 cm depth.³¹ As for peatlands, SOC stock estimates for permafrost are variable and have relatively high uncertainty. Mollisols, one of the main types of black soil, cover an estimated 7 percent of the ice-free land surface²⁸, but there is no current global estimate of their SOC content because they cover a large range of soil types and land uses.

SUB-THEME 3.2: SOILS IN GRASSLANDS AND LIVESTOCK PRODUCTION SYSTEMS

Grasslands cover approximately 40 percent of the earth's land surface^{32,33} and represent 70 percent of the global agricultural area, and they contain about 20 percent of the world's SOC stocks.¹ Grasslands characteristically have high inherent SOM content, averaging 333 Mg/ha,³⁴ and grassland soils are considered to have substantial potential to sequester even more carbon with improved grassland management practices and the rehabilitation of degraded grasslands. At the same time, such practices often increase the productivity and of grasslands and their resilience to climate variability.

Grasslands are under pressure in many regions, however, from increased grazing, inappropriate fire management, and the encroachment of other land-uses: for example, around 20 percent of the world's native grasslands have been converted to cultivated crops. There are considerable opportunities to benefit from management practices that sequester carbon in grasslands because large populations of people depend directly on grasslands but are often poor and vulnerable to climate variability and climate change. Implementing practices that increase grassland SOC stocks, therefore, could provide considerable mitigation, adaptation and development benefits.³⁴

Livestock production systems occupy about two-thirds of the world's agricultural land for the production of animal feed (80 percent for grazed pastures and 20 percent for the production of feed crops). With global demand for livestock products expected to double by 2050, especially in developing countries, it is increasingly important to improve forage-based systems and integrated systems of cropland–grassland–forest that contribute

to climate change adaptation and reduce carbon emissions associated with livestock production.³⁵ Strategies for sequestering carbon in grasslands also need to take into account the net balance of emissions under different management strategies, including emissions from livestock (enteric methane emissions) and their supply chains.

SUB-THEME 3.3: DRYLAND SOILS

Drylands (arid, semiarid and dry subhumid areas) are characterized by generally low average rainfall (where rainfall is less than the potential moisture losses through evaporation and transpiration), and they cover about 47 percent of the earth's land surface. Drylands are often associated with a lack of water, which severely constrains plant productivity and thus affects SOC accumulation in soils.³⁶ Nonetheless, dryland soils contain more than one-quarter of the global organic carbon store.²¹

Dryland soils are especially vulnerable to land degradation and desertification and associated SOC losses because SOC storage decreases with decreasing soil water content; dryland soils, therefore, contain low SOC stocks. The factors that influence SOC sequestration – such as climate, soil type, vegetation cover and management practices – are important in developing SOC management strategies and practices for these soils,³⁶ especially because their low SOC stocks represent high potential SOC sequestration given the large spatial extent of drylands.

Discussion Summary

Based on the differences in SOC and their varying sensitivity to management practices, five key questions were addressed.

Q3-1 Where are the priority areas for soil conservation to prevent SOC losses, and what are the associated policy requirements and incentives to regulate their sustainable management?

Priority areas for soil conservation:

From a GHG perspective, priority areas for the preservation of SOC stocks are those with the highest stocks. The higher the SOC stock, the higher the vulnerability of SOC to oxidation; this is the case, for example, for permafrost areas (although those are not managed directly) and peatlands. For peatlands, the two priority zones for protection were identified as 1) the vast areas of currently unmanaged (undisturbed) natural peatlands (about 80 percent of global peatlands are still considered pristine),³⁷ especially those in regions that are vulnerable to land-use change; and 2) peatlands of which the surface is intensively managed (e.g. for crop production or forestry).

To protect such peatlands, their location and extent needs to be known. The major constraint to advancing global peatland mapping is the scarcity of documented profiles of organic soils in general and of peatlands in particular, which prevents ground-truthing and accuracy assessments of continental and global-scale maps. Accuracy-validated maps are needed for land-use planning in peatlands. Soil data requirements include georeferenced data on soil carbon properties and soil moisture contents for measuring peat degradation.

From a food-security perspective, the priority is to conserve SOC in all soils used for food production, including grasslands used for grazing. This is especially true for dryland soils, where SOC stocks are often not high per unit land area. The preservation of SOC in such soils is crucial, therefore, for at least maintaining those soil functions related to food production supported by SOC.

Vulnerabilities in each land use depend on soil type, management practices, climate, and the social and economic conditions affecting management decisions. For example, vulnerability is higher in tropical peatlands where the benefits of cultivating them is very high, as well as in small patches of peatlands in the Mediterranean and other temperate areas subject to strong anthropogenic pressure. Therefore, priority areas should be defined at the national and local levels.

Policy requirements and incentives

Public policies and incentives are needed to support the protection and enhancement of SOC through management practices. Although management practices that protect or restore SOC have been shown to have simultaneous benefits for climate change mitigation and adaptation, food security and LDN, the introduction of such practices often has initial direct costs or causes an initial loss of revenue. This is due to a time-scale mismatch between the actions needed in the short term, the short-term constraints on actors such as farmers (the need for income), and the long time required to increase SOC stocks and obtain the associated benefits.

There is a need to better highlight the short-term benefits of sustainable SOC management and for short-term actions to enhance SOC that are compatible with farmers' activities. Incentives have to be specific and designed at the national and local scales, and they need to be customized according to the scale of application. For example, incentives to encourage the protection of existing SOC stocks in pristine ecosystems are not always the same as incentives for fostering sustainable practices in managed ecosystems. Incentives are particularly needed to promote the return of biomass and to outweigh competition for such biomass, such as use as fuel or fodder.

Farmers, particularly smallholders, do not prioritize carbon sequestration per se, but they may be willing to prioritize management options that enhance crop productivity and halt erosion and desertification, provided such practices are implementable and maintainable and that sufficient knowledge and capacity exists to support implementation. In many cases, additional incentives are needed to convince farmers to change from well-known practices to the new practices because it may involve changes in equipment, initial input costs, and more intensive management.

Q3-2 What are the realistically achievable SOC stock changes and rates of change for specific soils and land uses?

Participants indicated that this question could not be answered through discussion but, rather, required a thorough assessment to provide reliable values based on climate, soil type and management-specific conditions. Generally, however, the higher the SOC stock, the higher the rate of potential carbon losses following soil disturbance or change in land use (e.g. from forest or grassland to cropland).

For the three contexts considered in Theme 3 – soils with high SOC (peatlands, permafrost and black soils); grasslands and livestock production systems; and dryland soils – the priority is to maintain existing SOC stocks and minimize carbon losses. Even though it might be ambitious for diverse reasons to conserve existing stocks, it appears more realistic than increasing SOC stocks because SOC sequestration is generally a slow process, especially in soils with already-high SOC levels.

Q3-3 What is the degradation threshold where soil restoration and SOC sequestration is no longer considered feasible?

Participants suggested that a degradation threshold (tipping point) for SOC losses is an inappropriate concept. SOC losses are continuous and no degradation threshold can be defined, as it can be for other soil degradation types such as soil erosion and salinization. It may be possible, however, to define a degradation threshold in relation to the effectiveness of specific restoration measures because, in some cases, soils with very low SOC are unresponsive to restoration practices. Thresholds may also be defined in relation to the cost of restoration, for example when restoration becomes too costly to be economically viable – that is, the restoration of SOC-depleted soils is technically possible, but socio-economic factors impede its implementation (e.g. the cost of the necessary water, nutrients and biomass, etc.).

No universally applicable degradation threshold can be determined because it appears to be soil- and ecosystem-specific. However, in drylands, for example, soils are not responsive to inorganic fertilizers below a local threshold of SOC content, and increasing SOC or improving yields through the addition of inorganic fertilizers alone is not possible.

Rates of change are considered more important than thresholds. Data on rates of change exist and can be gathered and synthesized, for specific contexts.

The difference between restoration and rehabilitation was highlighted. *Restoration* refers to the recovery of ecosystems, including the pre-existing ecological structure and function. *Rehabilitation* can enable the recovery of SOC stocks but does not return ecosystems to their original pristine condition and characteristics (e.g. above-ground and below-ground biodiversity).

Q3-4 What are the potential derived ecosystem services and co-benefits of SOC sequestration that would contribute to climate change adaptation and reducing land degradation?

SOM contributes to many ecosystem services, such as the provision of food, fibre and fuel through its contribution to soil fertility; regulating the water cycle by increasing water infiltration and soil permeability; and the recycling of organic and other wastes. In addition, SOM helps sustain soil biodiversity and functional biodiversity, which, in turn, supports a range of provisioning soil ecosystem services. In addition to this general statement, which was confirmed for a variety of situations covered in Theme 3, the following specific points were raised:

- There can be benefits from adding organic material to soil without increasing SOC stocks. Examples include the addition of organic matter associated with improved soil fertility or resistance to erosion without changing SOC content. Beneficial SOC management should therefore not be limited to SOC sequestration.
- An increase in SOM does not always enhance productivity. In the case of peatlands, for example, there is a trade-off between conserving SOC and crop production and yields. It should be noted, however, that the latter (i.e. growing any kind of food in drained peat soils or using peat as a growth media) is unsustainable.
- In terms of managing GHG emissions from soils, the focus should not only be on carbon: N₂O emissions associated with certain high-SOC soils (such as some peatlands) should also be considered when planning appropriate management practices and GHG budgets.

Ecosystem services and the co-benefits of SOC sequestration should not only be considered at the plot or field scale, but also at larger scales, such as the landscape or territory scales (e.g. for erosion mitigation associated with enhanced SOC stocks).

Most benefits of SOC maintenance and sequestration are observed over the long term (decades), while farmers need benefits over the short term (months and years). There is a need to identify and highlight the short-term benefits of SOM to support the adoption of management practices that protect SOC from a production point of view.

Q3-5 What are the proven best management practices that prevent SOC losses and foster SOC sequestration?

Best management practices to prevent SOC losses and foster SOC sequestration are as follows:

- a. In peatlands: i) watertable regulation; ii) erosion control; iii) organic matter addition via inputs of plant biomass to soil or the addition of organic wastes; iv) no tillage if associated with permanent plant cover or increased biomass inputs to soil; and vi) peatland rewetting, focusing first on abandoned and drained peatlands.
- b. In grasslands: i) the introduction of a pasture phase into cropping cycles; and ii) addressing grassland species composition to ensure optimal species variety to reduce carbon losses and foster SOC sequestration.
- c. In drylands: i) integrated water and nutrient management (combining water with inorganic and organic amendments), thereby promoting a range of ecosystem benefits (such as crop yield increases) and often SOC sequestration; and ii) erosion control for SOC protection and sequestration (wind erosion is a significant problem in addition to water erosion).
- d. In all areas: maintaining groundcover.

Although increased additions of organic matter to soil are a major lever, there are important limitations to this approach, especially in dryland areas, including limits to the production of the necessary plant biomass (water and nutrient constraints), and competition with other biomass uses (such as fodder and fuel for domestic purposes).

As elaborated in Theme 2, farmers often know the practices and environmental benefits, but implementation is limited by cost. The priority for farmers is not to sequester carbon but, rather, to produce sufficient quantities of agricultural produce; even though SOC sequestration can help increase production, it is a slow and management-intensive process. More direct and short-term benefits are needed from SOC-sequestering practices, or a stronger evidence base for the short-term co-benefits of SOC sequestration and efficient and resilient food production needs to be developed and disseminated.

The VGSSM is generally compatible with the sustainable management of SOC. It is general in nature, however, and should be refined at the national and local scales to encompass site-specific conditions (climate, soil type, land use and farm typology, etc.).

Additional comments:

- Soil depth is an important consideration in the assessment of SOC because large SOC stocks and persistent organic matter exist in subsoils. However, standard reporting in terms of the 2006 IPCC Guidelines requires assessment only to a depth of 30 cm. It is important, therefore, to give sufficient attention to how management practices can increase SOC in deeper soil layers and how SOC can be assessed efficiently.
- SOM should not be reduced to SOC only, and it should not be overlooked that, in addition to carbon, SOM contains other elements, notably the nutrients nitrogen and phosphorus, that are indispensable for plant growth.
- SOC appears to be a good indicator of healthy soils, perhaps even the best, because it is meaningful, responsive, visible and measurable.
- Soil inorganic carbon should also be taken into account in the carbon balance, particularly in dryland soils, because its dissolution can be a significant source of CO₂ emissions and its secondary precipitation can contribute to climate change mitigation.

CONCLUSIONS AND WAY FORWARD

The GSOC17 brought together experts engaged in activities with FAO, the GSP and its ITPS, the IPCC, UNCCD-SPI and the WMO to work together for the common goal of appropriate SOC management as part of overall sustainable soil management and the agendas on climate change mitigation and adaptation, sustainable development, LDN and food security. Scientists from across the globe were active in presenting the results of studies demonstrating the potential and challenges of managing and monitoring SOC and discussing and developing the key messages reflected in this document. UN member countries and especially their policy advisors and decision-makers can actuate the implementation of the recommendations arising from this symposium.

Experts at the symposium concluded that there is convincing scientific evidence that a sustained increase in SOC contributes to the multiple objectives of climate change mitigation and adaptation, food security and achieving LDN. Often, there are synergies between climate change adaptation and mitigation and achieving LDN. Even when mitigation potential is not fully achieved due to interactions with other GHG fluxes, increasing SOC has crucial positive benefits for food security, climate change adaptation and achieving LDN by improving soil quality, reducing soil erosion and increasing soil water-holding capacity and drought resilience. Experts also agreed that the main priorities of the SOC agenda are preventing further SOC losses and, where feasible, providing incentives to increase SOC stocks. This can be achieved by avoiding or reducing soil and land degradation, supported, where possible, by increasing SOC. This strategy is consistent with the goal of LDN.

The symposium outcomes provide many examples of changes in land uses and land management that can help maintain or increase SOC. The outcomes also highlight the factors that determine the effectiveness of measures to increase SOC stocks in different environmental, socio-economic, cultural and institutional contexts, and they provide design principles for optimizing effectiveness. Although estimates of the global potential of SOC sequestration vary in magnitude depending on which land-use categories and GHG fluxes are included in assessments and the assumptions made on the impacts of practices on SOC stocks, the outcomes stress the strong potential for achieving SOC conservation and sequestration through appropriate soil and land management practices. The adaptation of sound and innovative practices to local conditions is essential to support this.

From the perspective of climate change mitigation, preventing SOC losses from carbon-rich soils such as peatlands, permafrost and black soils was identified as a priority due to the large amount of GHGs they can potentially release to the atmosphere. On the other hand, the conservation and enhancement of SOC stocks is important in all soils used for food production to maintain soil functions that ensure and improve food security. This applies to grasslands used for grazing and is especially important in drylands, which have a large spatial extent but often low SOC stocks per unit of land area.

Usually, land users are most concerned about yield enhancement and stability and thereby ensuring their livelihoods. Maintaining and increasing SOC stocks could be promoted, therefore, under the wider umbrella of sustainable soil management. The multiple long-term benefits of maintaining and increasing SOC stocks, such as greater food security and nutrition, poverty reduction, climate change adaptation, and achieving LDN and the SDGs, should serve as a global incentive for supporting decisions aimed at maintaining and increasing SOC. To encourage best SOC management practices by land users, however, tangible local incentives are needed.

The VGSSM were developed in an inclusive process and approved by FAO member countries. As part of their implementation and in order to progress with the realization of SOC conservation and sequestration in the field, symposium participants recommended that the guidelines be refined to provide context-specific guidance on the sustainable management of SOC at the national and local scales. To achieve this, a working group will be established in the GSP to coordinate the development of a technical and institutional manual on SOC management.

In making recommendations for SOC sequestration strategies, strong scientific confidence is necessary. Therefore, it was recommended that research focus on reducing uncertainties by analysing and promoting long-term experiments, validating results through meta-analyses, focusing geographically on understudied regions. An important activity in this regard was the launch of the International Network of Black Soils at GSOC17 with the aim of fostering technical collaboration to maintain the high SOC stocks of black soils worldwide.

The development of policy briefs would be useful for converting scientific evidence into accessible language to inform decision-making by member countries. Success stories and real-life examples of practices with the lowest uncertainties on their positive effects would be most effective. To achieve the large-scale implementation of SOC conservation and sequestration measures, the scientific community and policy- and decision-makers could engage in a participatory, interactive and iterative communication process with farmers, land users, landowners and extension services.

Extension services are crucial for bringing recommended management practices to users, such as through Soil Doctors and Farmer Field School programmes. Raising awareness of the benefits for landowners and the wider society of SOC and soil health is essential; this process commenced in the International Year of Soils and World Soil Day and should be nurtured.

The financial motivation for the large-scale implementation of sustainable soil and land management practices by land users and managers was mentioned several times during GSOC17. The specifications and risks of, and opportunities for, establishing additional incentives or financial agreements for the provision of ecosystem services through SOC maintenance and sequestration, including the creation of SOC markets, needs careful, holistic exploration.

It was recommended that countries be empowered by developing and strengthening national capacities related to the assessment, mapping, monitoring and reporting of SOC stocks over time and to soil management in general. Actions at the national level will take place when countries perceive their ownership of information, methods and results. Identifying and supporting national priorities and research focus, starting with direct users and involving local researchers in research activities, can foster such a sense of ownership.

One of the key activities of the GSP is the compilation of the GSOCMap, to be finalized by 5 December 2017, based on country-level soil datasets and nationally developed maps using harmonized specifications. In conjunction with this activity, it was recommended that a working group be established under the auspices of the GSP to facilitate collaboration among key scientific stakeholders, advisory panels and implementation bodies to develop feasible and regionally contextualized guidelines for measuring, mapping, monitoring and reporting on SOC. To support monitoring and reporting to conventions and the ultimate goal of enabling local and national decisions to improve soil carbon management, it was recommended that support be given to countries to increase capacity in the development of national reference values for SOC stocks and to improve data management capacities and facilities.

This outcome document, “Unlocking the potential of soil organic carbon”, will be submitted through appropriate channels to, among others, the 13th Conference of the Parties (COP13) of the UNCCD, COP23 of the UNFCCC, the GSP Plenary Assembly, the FAO Council, and COP14 of the Convention on Biological Diversity, and it will be made available to the IPCC for consideration at its Sixth Assessment Report scoping meeting.

REFERENCES

1. **FAO & ITPS**. 2015. The Status of the World's Soil Resources (Main Report). 648 pp. (also available at <https://hal.archives-ouvertes.fr/hal-01241064/>).
2. **Lawes, J.B. & Gilbert, J.H.** 1885. XLIV. On some points in the composition of soils; with results illustrating the sources of the fertility of Manitoba prairie soils. *Journal of the Chemical Society, Transactions*, 47(0): 380–422 (available at: <https://doi.org/10.1039/CT8854700380>).
3. **Lal, R.** 2013. Soil carbon management and climate change. *Carbon Management*, 4(4): 439–462 (available at: <https://doi.org/10.4155/cmt.13.31>).
4. **Batjes, N.H.** 2014. Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, 65(1): 10–21 (available at: https://doi.org/10.1111/ejss.12114_2).
5. **Hiederer, R. & Köchy, M.** 2011. Global soil organic carbon estimates and the harmonized world soil database. European Commission. Joint Research Centre, Institute for Environment and Sustainability.
6. **IPCC**. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change (IPCC).
7. **Scharlemann, J., Tanner, E.V.J., Hiederer, R. & Kapos, V.** 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Management*, 5(1): 81–91 (available at: <https://doi.org/10.4155/cmt.13.77>).
8. **FAO & ITPS**. 2016. Report of the Fifth Working Session of the Intergovernmental Technical Panel on Soils. Rome, FAO (available at: <http://www.fao.org/3/a-bl137e.pdf>).
9. **Orr, B.J., Cowie, A.L., Castillo Sanchez, V.M., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S., Tengberg, A.E., Walter, S. & Welton, S.** 2017. Scientific conceptual framework for land degradation neutrality. A report of the Science-Policy Interface. Bonn, Germany, United Nations Convention to Combat Desertification (UNCCD) (available at: http://www2.unccd.int/sites/default/files/documents/LDN_Scientific_Conceptual_Framework_FINAL.pdf).
10. **IPCC**. 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme. Volume 4 Agriculture, forestry and other land use. Intergovernmental Panel on Climate Change (IPCC) (available at: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html>).
11. **IPCC**. Undated. Decision IPCC/XLIV-5. Sixth Assessment Report (AR6) products, outline of the methodology report(s) to refine the 2006 Guidelines for National Greenhouse Gas Inventories Intergovernmental Panel on Climate Change (IPCC) (available at: https://www.ipcc.ch/meetings/session44/l3_adopted_outline_methodology_report_guideline.pdf).
12. **UN**. 2015. Paris Agreement. United Nations (UN) (available at: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf).
13. **UNCCD**. 2016. Indicator 15.3.1: Proportion of land that is degraded over total land area. United Nations Convention to Combat Desertification (UNFCCC) (available at: http://www.unccd.int/Lists/SiteDocumentLibrary/Rio+20/LDN_2016/UNCCD_15.3.1_metadata_04_March_2016.pdf).

14. **United Nations Convention to Combat Desertification, Convention on Biological Diversity, FAO & Scientific and Technical Advisory Panel of the Global Environment Facility.** 2016. Framework and guiding principles for a land degradation indicator data from multiple sources. 2.2 Guiding principles. 3.0 Definitions, methodologies and data options (available at: [http://www.unccd.int/Lists/SiteDocumentLibrary/Rio+20/LDN_2016/Framework and Guiding Principles for a Land Degradation Indicator.pdf](http://www.unccd.int/Lists/SiteDocumentLibrary/Rio+20/LDN_2016/Framework_and_Guiding_Principles_for_a_Land_Degradation_Indicator.pdf)).

15. **Lorenz, K. & Lal, R.** 2016. Soil organic carbon: an appropriate indicator to monitor trends of land and soil degradation within the SDG framework? Dessau-Roßlau, Germany (available at: http://www.umweltbundesamt.de/sites/default/files/medien/1968/publikationen/2016-11-30_soil_organic_carbon_as_indicator_final.pdf).

16. **UNFCCC.** 2014. Handbook on measurement, reporting and verification for developing countries. Bonn, Germany, United Nations Framework Convention on Climate Change (UNFCCC) (available at: https://unfccc.int/files/national_reports/annex_i_natcom_/application/pdf/non-annex_i_mrv_handbook.pdf).

17. **Batjes, N.H.** 2011. Soil organic carbon stocks under native vegetation: revised estimates for use with the simple assessment option of the Carbon Benefits Project system. *Agriculture, Ecosystems & Environment*, 142(3): 365–373 (available at: <https://doi.org/10.1016/j.agee.2011.06.007>).

18. **Hengl, T., Mendes de Jesus, J., Heuvelink, G.B.M., Ruiperez Gonzalez, M., Kilibarda, M., Blagoti, A., Shangquan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., Guevara, M.A., Vargas, R., MacMillan, R.A., Batjes, N.H., Leenaars, J.G.B., Ribeiro, E., Wheeler, I., Mantel, S. & Kempen, B.** 2017. SoilGrids250m: global gridded soil information based on machine learning. *PLOS ONE*, 12(2): e0169748 (available at: <https://doi.org/10.1371/journal.pone.0169748>).

19. **Totsche, K.U., Rennert, T., Gerzabek, M.H., Kögel-Knabner, I., Smalla, K., Spiteller, M. & Vogel, H.-J.** 2010. Biogeochemical interfaces in soil: the interdisciplinary challenge for soil science. *Journal of Plant Nutrition and Soil Science*, 173(1): 88–99 (available at: <https://doi.org/10.1002/jpln.200900105>).

20. **Pribyl, D.W.** 2010. A critical review of the conventional SOC to SOM conversion factor. *Geoderma*, 156(3): 75–83 (available at: <https://doi.org/10.1016/j.geoderma.2010.02.003>).

21. **UNCCD-SPI.** 2015. Pivotal soil carbon. Science-Policy Brief 01. United Nations Convention to Combat Climate Change Science-Policy Interface (UNCCD-SPI) (available at: http://www.unccd.int/Lists/SiteDocumentLibrary/Publications/2015_PolicyBrief_SPI_ENG.pdf).

22. **Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., Courcelles, V. de R. de, Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D. & Zimmermann, M.** 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems and Environment*, 164: 80–99 (available at: <https://doi.org/10.1016/j.agee.2012.10.001>).

23. **Lehmann, J. & Kleber, M.** 2015. The contentious nature of soil organic matter. *Nature*, 528(7580): 60–8 (available at: <https://doi.org/10.1038/nature16069>).

24. **Trumbore, S.E. & Czimczik, C.I.** 2008. An uncertain future for soil carbon. *Science*, 321(September): 1455–1456 (available at: <https://doi.org/10.1126/science.1160232>).

25. **Lal, R.** 2003. Offsetting global CO₂ emissions by restoration of degraded soils and intensification of world agriculture and forestry. *Land Degradation and Development*, 14(3): 309–322 (available at: <https://doi.org/10.1002/ldr.562>).

26. **Sommer, R. & Bossio, D.** 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*, 144: 83–87 (available at: <https://doi.org/10.1016/j.jenvman.2014.05.017>).

27. **FAO.** 2017. Soil organic carbon: the hidden potential. Rome (available at: <http://www.fao.org/3/a-i6937e.pdf>).

28. **Liu, X., Lee Burras, C., Kravchenko, Y.S., Duran, A., Huffman, T., Morras, H., Studdert, G., Zhang, X., Cruse, R.M. & Yuan, X.** 2012. Overview of mollisols in the world: distribution, land use and management. *Canadian Journal of Soil Science*, 92(3): 383–402 (available at: <https://doi.org/10.4141/cjss2010-058>).

29. **Köchy, M., Hiederer, R. & Freibauer, A.** 2015. Global distribution of soil organic carbon. Part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. *Soil*, 1(1): 351–365 (available at: <https://doi.org/10.5194/soil-1-351-2015>).

30. **Buffam, I., Carpenter, S.R., Yeck, W., Hanson, P.C. & Turner, M.G.** 2010. Filling holes in regional carbon budgets: predicting peat depth in a north temperate lake district. *Journal of Geophysical Research*, 115(G1): 1–16 (<https://doi.org/10.1029/2009JG001034>).

31. **Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.L., Schirmer, L., Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J.A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J. & Kuhry, P.** 2014. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, 11(23): 6573–6593 (available at: <https://doi.org/10.5194/bg-11-6573-2014>).

32. **Mcsherry, M.E. & Ritchie, M.E.** 2013. Effects of grazing on grassland soil carbon: a global review. *Global Change Biology*, 19(5): 1347–1357 (available at: <https://doi.org/10.1111/gcb.12144>).

33. **Orgiazzi, A., Bardgett, R.D., Barrios, E., Behan-Pelletier, V., Briones, M.J.I., Chotte, J-L., De Deyn, G.B., Eggleton, P., Fierer, N., Fraser, T., Hedlund, K., Jeffery, S., Johnson, N.C., Jones, A., Kandeler, E., Kaneko, N., Lavelle, P., & Lemanceau, P., M, D.** 2016. *Global Soil Biodiversity Atlas*.

34. **Conant, R.T. & FAO.** 2010. Challenges and opportunities for carbon sequestration in grassland systems: a technical report on grassland management and climate mitigation. Rome, FAO (available at: <http://www.fao.org/docrep/012/i1399e/i1399e00.htm>).

35. **Gaitán, L., Läderach, P., Graefe, S., Rao, I. & van der Hoek, R.** 2016. Climate-smart livestock systems: an assessment of carbon stocks and GHG emissions in Nicaragua. *PLOS ONE*, 11(12): e0167949 (available at: <https://doi.org/10.1371/journal.pone.0167949>).

36. **Sharma, P., Abrol, V., Abrol, S. & Kumar, R.** 2012. Climate change and carbon sequestration in dryland soils. In V. Abrol & P. Sharma, eds. *Resource management for sustainable agriculture*. InTech (available at <http://www.intechopen.com/books/resource-management-for-sustainable-agriculture/climate-change-and-carbon-sequestration-in-dryland-soils>).

37. **Barthelmes, A., Couwenberg, J., Risager, M., Tegetmeyer, C. & Joosten, H.** 2015. Peatlands and climate in a Ramsar context. A Nordic-Baltic perspective. Nordic Council of Ministers (available at: <http://urn.kb.se/resolve?urn=urn:nbn:se:norden:org:diva-3927>).



WITH THE FINANCIAL SUPPORT OF



MINISTRY FOR FOREIGN AFFAIRS
OF ICELAND



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs,
Education and Research EAER
Federal Office for Agriculture FOAG

ISBN 978-92-5-109759-5



9 789251 097595

I7268EN/1/05.17