Food and Agriculture Organization of the United Nations

GSOC MRV Protocol

A protocol for **measurement**, **monitoring**, **reporting** and **verification** of **soil organic carbon** in agricultural landscapes

itps
INTERGOVERNMENTAL TECHNICAL PANEL ON SOILS

September 2020

GLOBAL SOIL PARTNERSHIP

GSOC MRV Protocol

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Contents

Tables

Figures

Photos

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Foreword

Climate change, population growth, urban sprawl, increasing global food insecurity, changing diets and biodiversity loss are only some of the challenges currently faced by humankind. In addition, there are rising concerns from mounting pollution and associated impacts, as well as the steady increase in land degradation and desertification. Most recently, the COVID-19 pandemic has added a new global challenge, testing the resilience of our societies to adapt, at all levels, in times of hardship.

The global nature of this crisis sheds new light on how our ability to ensure food security and provide key ecosystem services inherent to soils, such as the provision of food, fiber and fuel, climate regulation and carbon sequestration, will increasingly depend on the availability of healthy and sustainably managed soils.

Soils are the foundation for food production and many essential ecosystem services. Soils have become one of the key resources for climate change mitigation and adaptation, as they constitute the main carbon reservoir in terrestrial ecosystems. Soil organic carbon (SOC), as an essential component of soil health, plays a key role in the overall behavior of soils, ecosystems and agroecosystems. Increasing its content enhances overall soil health and fertility, the resilience and sustainability of agriculture and, in turn, improves food security and nutrition for all. The role of soils and SOC in the climate system, and especially in climate change adaptation and mitigation, has been widely recognized and scientifically validated.

The Paris Agreement, the Koronivia Joint Work in Agriculture and the recent Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate and Land, have also led to the development of an enabling political-institutional environment that will allow the support and adoption of sustainable management practices based on SOC maintenance and/or sequestration.

In addition, in the context of the Sustainable Development Goals (SDGs), a sustainable global food system must foster a sustainable environment in which agriculture, biodiversity conservation and climate change adaptation and mitigation can thrive, but also co-exist and complement each other.

As part of the SDGs, SDG 15 "Life on Land" includes soil in 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 SDG indicator 15.3.1 *"Proportion of land that is degraded over total land area"* is based on three sub-indicators and associated metrics: land cover (land cover change), land productivity (land productivity dynamics) and carbon stocks (soil organic carbon stocks).

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In 2017, FAO, the Global Soil Partnership (GSP), Intergovernmental Technical Panel on Soils (ITPS), IPCC, UNCCD-SPI (The Science-Policy Interface of the United Nations Convention to Combat Desertification) and the World Meteoroligcal Organization (WMO) jointly organized a Global Symposium on Soil Organic Carbon. The Symposium provided an opportunity to review the important role of soils and SOC in the context of climate change adaptation and mitigation, sustainable development and land degradation neutrality. The resulting outcome document focused on clear and practical recommendations on the way forward, including to establish a working group, under the guidance of the ITPS to develop a protocol for measuring, reporting, verification and monitoring of SOC sequestration and greenhouse emissions in agricultural landscapes.

Since then, FAO and the GSP launched RECSOIL: Recarbonization of Global Soils Programme, a comprehensive tool to scale up sustainable soil management practices based on SOC sequestration.

Measuring, monitoring, reporting and verifying (MRV) the addition and permanence of SOC constitutes a crucial step for any project dealing with carbon farming, climate finance and to support indicator SDG 15.3.1 using a thorough analysis applicable at field level.

This MRV protocol, which has been developed through an extensive research and consultation process, involving scientists, policy makers, FAO Members, and international and intergovernmental panels, provides a standardized tool to support SDG 15.3.1., as well as any project related to SOC sequestration and the newly launched RECSOIL initiative.

It is my hope that this voluntary protocol will support the widespread adoption of sustainable soil management practices for healthy soils and help protocol users to reliably measure their success in sequestering carbon in the fight against climate change and in the provision of other key ecosystem services. This will be a great contribution to achieving the SDGs.

Maria Helena Semedo

Deputy Director-General
Food and Agriculture Organization of the United Nations


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Preface

The document is an outcome of the successful Global Symposium on Soil Organic Carbon (GSOC17), which was held in Rome in March 2017. The symposium was jointly organized by FAO, GSP and ITPS, IPCC, UNCCD-SPI and WMO.

The GSOC17 Outcome Document "Unlocking the potential of soil organic carbon" contained a number of recommendations for the way forward. One of the recommendations called for the establishment of 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.

Accordingly, this GSOC-MRV working group was established via an open call of experts and, under the guidance of the ITPS, was tasked to prepare a draft MRV (measurement, reporting, verification) protocol for consideration and review by various panels and experts.

An *open call for experts* was launched in March 2018 and 124 experts from all regions in the world responded to it. This working group started by preparing the draft table of contents; authors were then selected for the different sections of the protocol.

A zero draft was prepared and submitted for consideration by the ITPS. The ITPS made substantial suggestions for improvement and a comprehensive first draft was prepared by the GSOC-MRV working group.

This first draft was then submitted for review to the Science Policy Interface of the United Convention to Combat Desertification, the Committee of Science and Technology of the 4/1000 initiative and the Coordination of International Research Cooperation on Soil Carbon Sequestration (CIRCASA) consortium. Very extensive feedback was received with recommendations for improving the GSOC-MRV Protocol.

A second draft was then prepared by the GSOC-MRV Working Group that incorporated the suggestions and recommendations made from all parties in the process. This final draft was submitted for consideration of the Eighth GSP Plenary Assembly. This GSOC-MRV was endorsed by the Plenary Assembly, which was held on 3 to 5 June 2020.

It should be noted that this is a technical document in support of the Soil organic carbon (SOC) sequestration work and that its use is not mandatory but is strictly voluntary.

We hope members and partners will make full use of this GSOC-MRV as a voluntary protocol for measuring soil organic carbon stocks and changes in agricultural landscapes.

Acknowledgements

The GSOC-MRV Protocol "A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes" is the result of a very inclusive and collaborative work of scientists from many countries around the world, international organizations, panels, initiatives and institutions.

We express our sincere gratitude to the SOC working group that was established to draft this fundamental tool.

Furthermore, we would like to thank all the reviewers (individuals and panels) who provided insights, suggestions, and recommendations to enhance the document in an iterative process. FAO Members are especially recognized for their contribution to the preparation and careful review of this document.

Special thanks go to Professor Pete Smith (University of Aberdeen) for guiding the preparation of this protocol and for his exhaustive review.

The UNCCD-SPI, the SCT-4/1000 and the CIRCASA (Coordination of International Research Cooperation on Soil Carbon Sequestration in Agriculture) platform are acknowledged for their in-depth review process to improve the quality of this protocol.

Finally, we recognize the leading scientific role of the Intergovernmental Technical Panel on Soils (ITPS) and the Pillar 4 Working Group (P4WG) in overseeing the science behind this protocol.

Abbreviations and acronyms

BAU: Business as usual

BD: Bulk Density

C: Carbon

CO_2-eq: equivalent carbon dioxide, resulting from multiplying GHG emissions times their global warming potential (CO_2 = 1; N_2O = 295; CH_4 = 25)

DM: Dry matter

DOC: Dissolved organic carbon

ESM: Equivalent soil mass

GHG: Greenhouse Gases (CO_2 = carbon dioxide; N_2O= nitrous oxide; CH_4 = methane)

GLOSOLAN: Global Soil Laboratory Network

GSOCMap: Global Soil Organic Carbon Map

GSOCSeq: Global Soil Organic Carbon Sequestration Map

IA: Intervention Area

IPCC: Intergovernmental Panel on Climate Change

IS: Intervention scenario

MDD: The minimal detectable difference

MRV: Monitoring, Reporting and Verification

POC: Particulate organic carbon

R: Greenhouse gases emovals (in CO_2-eq)

SIC: Soil inorganic carbon

SOC: Soil organic carbon

SOC-decreasing: Decreasing soil organic carbon

SOC-equilibrium: Soil organic carbon in equilibrium

SOC-increasing: Increasing soil organic carbon

SOCseq: Soil organic carbon sequestration

SOM: Soil organic matter

SON: Soil organic nitrogen

SSM: Sustainable Soil Management

QA/QC: Quality assurance (QA) and quality control (QC)

Pexels

1 Introduction

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. The role of soils and of soil organic carbon (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. Maintaining and increasing SOC stocks is not only crucial for reducing GHG emissions and removing CO_2 from the atmosphere, but also for harnessing the benefits of increased SOC (and SOM, soil organic matter) 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 (FAO, 2017b). Loss of SOC may lead to changes in health threat to human beings (Wu *et al.*, 2016), and poses a significant challenge to rural communities and to our ability to thrive on our planet.

Adoption of site-specific Sustainable Soil Management (SSM) practices in agricultural lands can harness a large C sink capacity at a global scale, and it has been highlighted as a significant greenhouse gas (GHG) removal strategy (Lal *et al.*, 2018; Smith *et al.*, 2020; Paustian *et al.*, 2019). It has been estimated that the global technical potential of terrestrial C sequestration is between 1.7 and 4.6 Pg C/year (Lal *et al.*, 2018). Sequestration rates due to management practices in agricultural lands are usually in the range of 0.2 to 0.8 t C/ha/year (Poepleau and Don, 2015; Kampf *et al.*, 2016; Minasny *et al.*, 2017; Conant *et al.*, 2017; Paustian *et al.*, 2016; Paustian *et al.*, 2019). The magnitude and rate of carbon sequestration in soils can vary greatly, depending on the different land uses and practices, soil characteristics, vegetation, topography and climate, among other soil forming factors and processes (Smith *et al.*, 2008; Minasny *et al.*, 2017; Lal *et al.*, 2018; Batjes, 2019), which add to the many challenges for quantifying SOC stocks and changes.

As highlighted by Smith *et al.* (2020) the absence of monitoring, reporting and verification (MRV) procedures is a key barrier to implementing programs oriented to increasing SOC at large scale, impeding investments to mitigate GHG emissions. Soil organic carbon and GHG standard quantification schemes have been developed at national scales (IPCC, 2006), but less attention has been directed to platforms designed to be implemented at farm level. Although there are private and public farm-scale oriented MRV protocols and platforms (such as the Australian Government Carbon Farming Initiative; Alberta-Canada Government Conservation Cropping Protocol; USDA's COMET; Verified Carbon Standard Protocols; Gold Standard Soil Organic Carbon Framework Methodology), each platform focuses on different productive systems and different specific management practices that can influence SOC, uses different methods and models to quantify and monitor SOC changes and GHG emissions, and applies different approaches and timescales to consider the effects of management practices, and/or is applicable only to specific geographical locations. The Food and Agriculture Organization of the United Nations (FAO) itself, through the Livestock Environmental Assessment and Performance Partnership (LEAP), produced guidelines for measuring and modelling soil organic carbon stocks and stock changes in livestock production systems (FAO, 2019a).

The national monitoring of and reporting on SOC is becoming increasingly important in the fulfilment of global conventions and mechanisms. 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 (FAO, 2017b). There is a growing need for standardized, robust, reliable, cost-effective and easily applicable MRV platforms for SOC change and GHG removals, applicable to different agricultural systems around the world. FAO's Global Soil Partnership, together with partners, organized the Global Symposium on Soil Organic Carbon that yielded the Outcome Document: "Unlocking the potential of soil organic carbon." This document contained

a number of key recommendations for the way forward. One of the recommendations was related to the establishment of 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 and ultimately to support management decisions. This GSOC-MRV protocol aims at meeting that need and was developed through an inclusive and active process involving experts and institutions from all regions of the world. **This protocol does not constitute a mandatory document for FAO members or institutions, but is rather a guiding, non-binding technical document to support the MRV work.** As a living document, its continuous improvement and refinement is expected after its use and implementation in the field.

2 Objectives and scope

The objective of this document is to provide a conceptual framework and standard methodologies for the monitoring, reporting and verification of changes in SOC stocks and GHG emissions/removals from agricultural projects that adopt Sustainable Soil Management practices (SSM) at farm level. It is intended to be applied in different agricultural lands, including annual and perennial crops (food, fibre, forage and bioenergy crops), paddy rice, grazing lands with livestock including pastures, grasslands, rangelands, shrublands, silvopasture and agroforestry. Although developed for projects carried out at farm level, potential users include investors, research institutions, government agencies, consultants, agricultural companies, NGOs, individual farmers or farmer associations, supply chain and other users who are interested in measuring and estimating SOC stocks and changes and GHG emissions in response to management practices.

3 Monitoring, reporting and verification protocol overview

The protocol consists of a series of step-by-step stages and sub-protocols in order to assess SOC changes and GHG emissions/removals by the adoption of SSM practices (Figure 1). The first stage (S1: Applicability conditions) is intended to verify that the project and activities meet the necessary requirements for this methodology to be applicable. Scale, eligible and restricted lands, land uses and management practices are detailed in Section 4 of this report. The project spatial and temporal boundaries shall be specified during a second stage (S2: Boundaries), as described in Section 5. In a third stage (S3: Baseline and intervention scenarios delineation), the baseline and projected intervention management scenarios and practices shall be defined, indicating historic and projected relevant activity data for the different areas to be assessed (e.g. areas, crops, yields, tillage practices, fertilizer use, organic amendment use, livestock density). Information and methods required to define the baseline and intervention practices are detailed in Section 6. In a fourth stage, (S4: Additionality assessment) a preliminary assessment of the additionality of the projected practices shall be performed (that is, how much carbon would be sequestered in soils and how much GHG emissions will be reduced, compared to a situation in which the proposed technologies or changes would not have existed). In order to do this, process-oriented SOC modelling activities and standardized methodologies to estimate key agricultural GHG emissions are delineated. This shall be performed before implementing time- and resource-demanding monitoring schemes. The general methods to estimate additionality are described in Section 7, and modelling and GHG estimation sub-protocols are provided in the Annex sections. Once additionality is assessed, the fifth stage (S5: Monitoring) shall be implemented to monitor the implemented practices. General monitoring methodologies are described in Section 8, and soil-sampling sub-protocols are provided in the Annex sections. In addition, SOC stocks shall be projected using the activity

data of the performed practices and the same specified SOC models and GHG emissions methods used in the preliminary assessment. Concurrently, bi-annual reports shall be delivered (S6: Reporting) indicating performed activities, soil sampling results and modelling estimates, following the procedures described in Section 9.

3.1 Responsibilities and organization

A crucial aspect is who is responsible for each part of an MRV and, in this sense, it is important to clarify that the individuals or companies who are in charge of carrying out monitoring and reporting cannot also carry out the verification. Those who submit projects to dedicated schemes such as RECSOIL (Re-carbonization of global soils to offset global emissions GSP-FAO program) require reporting not only the additionality of the project (how much carbon would be sequestered compared to a situation in which the proposed technologies or changes would not have existed), but also the periodic changes in carbon. For this purpose, it is required to do the monitoring and reporting activities, which can be carried out by the same person or entity. This person or entity is the one that accompanies the farmer in the presentation of his/her project and, necessarily, must be endorsed by a curriculum vitae (CV) and professional registration, or national type of accreditation. It will be their responsibility to present the proposal, carry out the sampling rounds and prepare and present the reports.

The subsequent stage is that of verification and, also necessarily, it will be carried out by other people or entities accredited by FAO and participating national institutions in dedicated schemes such as RECSOIL. This requirement ensures independence between the person who presents the project and the one who evaluates it and, eventually, contributes the funds to finance the farmers. This is the case, for example, in other verification processes, such as the QA / QC (quality assurance / quality control) processes of the IPCC Guidelines (IPCC, 2006), which although they can (and should) be carried out by the same team that performs a GHG inventory, inevitably there must always be an external and independent QA / QC process.

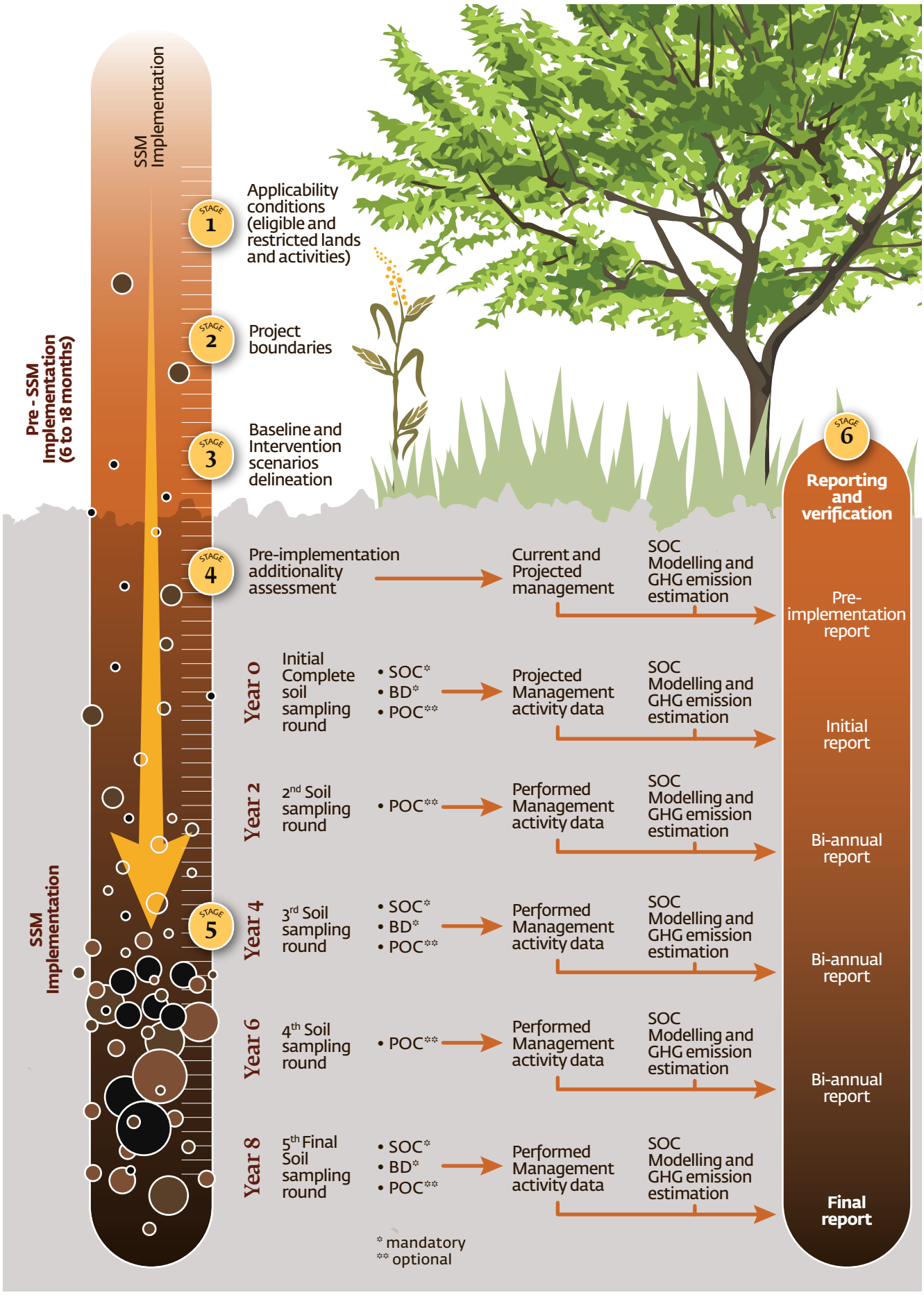

Figure 1 | Stages and processes of the MRV Protocol.

4 Stage 1: Conditions for determining protocol applicability

This MRV is applicable to farm-scale projects that introduce designated Sustainable Soil Management (SSM) practices in defined agricultural lands, under specified conditions. This stage is intended to verify that the project and activities meet the necessary requirements for this protocol to be applicable.

4.1 Scale

This MRV Protocol shall be applicable at the farm scale in defined intervention areas (IAs). Each IA may involve one or several fields, plots or paddocks, either within one individual farm or on different farms owned or operated by the same or different companies that are part of the same project. If one part of the project area is materially different to another, more than one IA shall be defined due to the increased likelihood of detecting SOC changes in SOC in homogeneous IAs. Material differences in soil type, land use, land-use history and landform all affect SOC stocks and, thus, shall trigger delineation of separate IAs.

4.2 Eligible and restricted lands

Eligible lands are either croplands and grazing lands at the start of the project, that show the potential for improvement in their soil organic carbon stock after the adoption of SSM practices (compared to business as usual practices), by either gaining or maintaining SOC levels. Four situations are possible: a) lands where SOC levels have reached equilibrium and it is possible to increase levels through SSM; b) lands where the SOC is increasing but can be further increased through SSM; c) lands where SOC is declining and it is possible to stop or mitigate losses in SOC levels through SSM; and d) lands where SOC is declining and it is possible to reverse this fall through SSM. These situations are depicted in Figure 2.

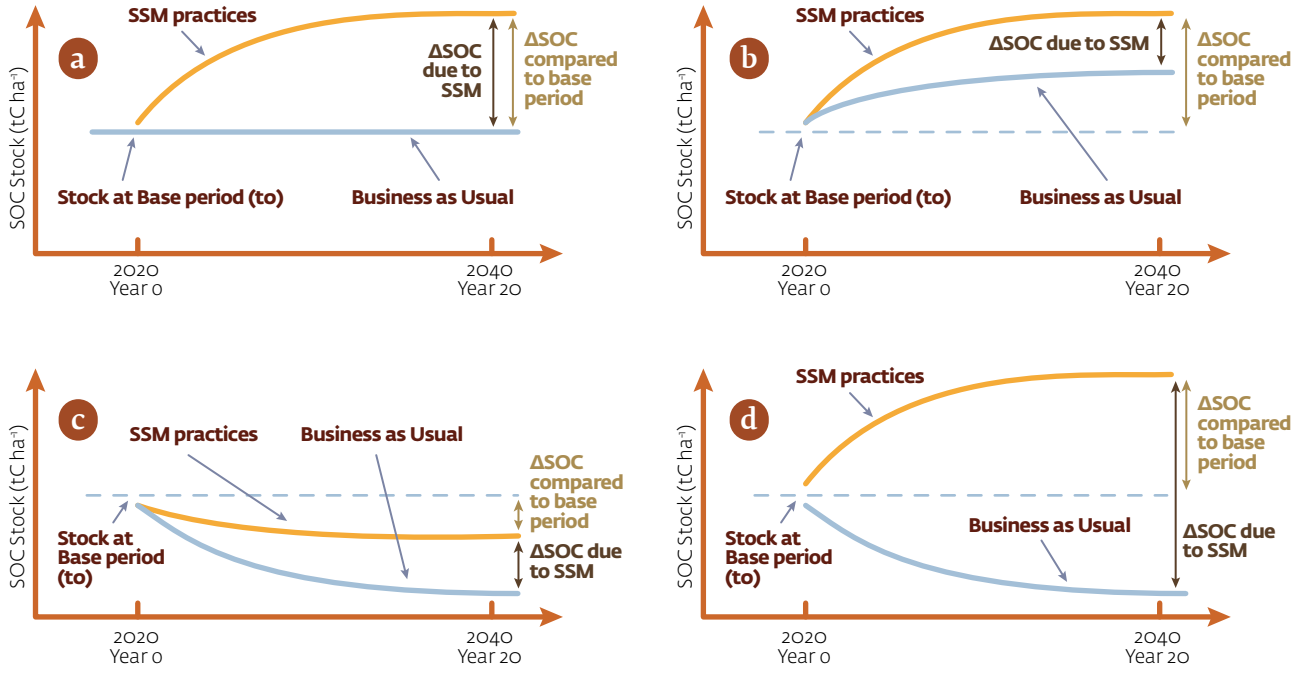

Figure 2 | Soil organic carbon theoretical evolutions under a business-as-usual (BAU) scenario and after the adoption of Sustainable Soil Management (SSM) practices. This depicts a) lands where SOC levels have reached equilibrium and it is possible to increase levels through SSM; b) lands where SOC is increasing but can be further increased through SSM; and lands where SOC is decreasing and it is possible to stop or mitigate losses in SOC levels (c), or even reverse this fall through SSM (d).

In order to avoid potential damage to biodiversity-rich lands, this protocol is only applicable if practices are not implemented on these conditions:

a) wetlands and peatlands, or lands that have been subject to the drainage of a wetland/peatland during a baseline period (past ten years) or other baseline periods determined by obligations under national and international legislation;

b) organic soils, Histosols, or soils having a histic or folic horizon (FAO, 2015);

c) current native forest lands, or lands that have been native forest lands and were converted to grasslands or croplands, at any point during a baseline period (at least past ten years), or other baseline periods determined by obligations under national and international legislation.

4.3 Eligible and restricted intervention practices

The intervention practices shall be based on the Voluntary Guidelines for Sustainable Soil Management (VGSSM) principles, which provide guidance to a wide range of stakeholders (FAO, 2017a). In these guidelines, Sustainable Soil Management is defined according to Principle 3 in the revised World Soil Charter as follows: *"Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity."*

Based on – but necessarily restricted to – the recommended practices described in VGSSM and in the Technical Manual on SOC Management (FAO-GSP, under development) that are aimed at increasing SOC levels, eligible practices under this protocol may include:

a) Increase in biomass production by managing water availability for plants with soil water conservation practices and adequate and efficient irrigation management;

b) Balanced fertilizer applications with appropriate and judicious fertilizer application methods, types, rates and timing, following the International Code of Conduct for the Use and Management of Fertilizers (FAO, 2019b);

c) Effective use of organic amendments (such as animal manure, plant residues, compost, digestates, biochar), following the International Code of Conduct for the Use and Management of Fertilizers (FAO, 2019b);

d) Effective use of inorganic amendments (e.g. lime or gypsum to remediate acid soils, gypsum to remediate sodic soils), following the International Code of Conduct for the Use and Management of Fertilizers (FAO, 2019b); integrated soil fertility management (combined application of inorganic and organic nutrient resources/fertilizers);

e) Soil health improvement with biofertilizers (beneficial microbes), such as mycorrhiza, phosphate solubilizing bacteria, bio-inoculants and bio-inducers;

f) Crop residue management: applying organic residues, mulches or providing the soil with permanent cover;

g) Use of cover crops or green manure, and/or perennials in crop rotations; establishing a pasture in croplands or bare fallow;

h) Reduction of tillage events and or the adoption of residue management techniques, minimum or no-tillage;

i) Implementation of practices oriented to prevent and/or alleviate soil compaction (e.g. controlled traffic operations; 'bio-drilling' by using tap-root species; judicious subsoiling labours);

j) Grazing management to promote soil vegetation cover (stocking rate, grazing duration and intensity); rejuvenating pastures by seeding;

k) Implementation and diversification of crop rotations, integration of production systems (for example, crop-livestock, silvopastoral, agroforestry), use of improved species (such as deep rooting and tap rooting crops);

l) Landscape management modification such as those implemented for erosion control (such as terraces), surface water management, and drainage/flood control;

m) Planting indigenous species (for example, N_2 fixing legumes) adapted to local ecological conditions on degraded or abandoned croplands.

It is worth highlighting that this MRV protocol does not prescribe any management practice.

This MRV protocol does not apply for the following practices:

a) drainage of wetlands;

b) topsoil removal for industrial or other purposes (e.g. bricks factories);

c) landscape modifications that are not oriented to erosion control (e.g. slope reshaping practices in industrial vineyards);

d) the use of products that add substances at potentially toxic levels into soils and water: heavy metals, radioactive elements and pathogens;

e) replacement of permanent native perennial vegetation by annual vegetation (e.g. deforestation, conversion of native grasslands, rangelands, shrublands);

f) overgrazing and all agricultural transit resulting in excessive compaction;

g) the use of fire as a management tool, except where fire is a naturally occurring event, or is integral to land management (such as controlled fire use), in which case the timing and intensity of burning should aim to limit losses of soil functions, and steps to minimize erosion and encourage revegetation after fire should be considered.

4.4 Leakage

Leakage refers to indirect GHG emissions or SOC losses that can occur outside the project's boundaries but are still attributable to the project's activities. For example, a project that aims at converting areas under croplands to permanent grasslands in order to enhance SOC sequestration but which indirectly results in deforestation or converting other areas under grasslands to croplands in a region or area outside the declared boundaries causes leakage (see Section 5). This MRV protocol does not apply to projects where leakages due to land use changes are generated or are expected to be generated by project participants. Although this protocol is not oriented to estimate GHG emissions beyond the delineated project boundaries (for example, emissions associated with the overseas transport of fertilizers or other inputs or products), potential sources of leakage other than land use changes shall be outlined during this initial stage.

4.5 Permanence and reversals

Soil organic carbon is one of the most stable forms of carbon in nature and positively correlates directly with soil structure stability, water and nutrient availability to plants and, therefore, to plant growth, soil health, microbial biodiversity and crop yields. Organic carbon is physically, biologically and chemically stabilized within soils and has residence times ranging from decades to centuries. However, SOC can be lost from soils in different ways: a) as carbon dioxide and methane into the atmosphere; b) as SOC in erosive processes, and c) as dissolved organic carbon (DOC) in deep percolating water (leaching losses). These losses are expected to occur at lower rates if Sustainable Soil Management practices are applied, but the SSM plan must be designed to ensure that emissions reductions will persist over the life of the project, and that soil organic carbon that was stored in soils has a low risk to be re-emitted to the atmosphere as CO_2. As a result, disturbances and events that can cause reversals (CO_2 re-emissions) must be considered. During this initial stage of determining the applicability of this protocol, projects shall identify the internal, external, and natural risks for reversals, and then outline how the project plans to mitigate these risks. In addition, a 5 percent risk of reversal discount shall be applied to all sequestration/removal projects.

Restricted lands

This protocol does not apply to lands that have been native forest lands and were converted to grasslands or croplands, at any point during a baseline period.

Native forest being cleared for agriculture, Chaco, Argentina

Elegible practices

Increase in biomass production by managing water availability.

Irrigated maize in Valle Medio Rio Negro, Patagonia, Argentina

Elegible practices
Use of perennials in crop rotations.
Crop-pasture rotation

Elegible practices
Increase in biomass production by managing water availability

Elegible practices
Use of cover crops in crop rotations.
Roots from hairy vetch used as cover crop

Elegible practices
Use of cover crops in crop rotations.
Vetch as cover crop, 100% soil coverage

Elegible practices
Use of cover crops in crop rotations.
Roots from rye as cover crop

Elegible practices
Use of cover crops in crop rotations.
Avena estrigosa as cover crop, Corrientes, Argentina

Elegible practices
Use of cover crops in crop rotations.
Hairy vetch and triticosecale mixture as cover crop

Elegible practices
Use of cover crops in crop rotations.
Hairy vetch as cover crop

Elegible practices
Use of cover crops in crop rotations.
Hairy vetch as cover crop

Elegible practices
Diversification of crop rotations.
Use of tap rootind species like rapeseed as cover crops

Elegible practices
Diversification of crop rotations.
Wheat growing in maize residues

Elegible practices
Integration of production systems (livestock-agriculture)

Elegible practices
Integration of production systems (livestock-agriculture), inclusion of perennials in crop rotations.
Las Lajitas, Argentina

Elegible practices
Inclusion of perennials in crop rotations.
Gatton panic roots after 6 months of implanted

Elegible practices
Crop residue management: providing the soil with permanent cover.
Maize growing over wheat residues

Elegible practices
Crop residue management: providing the soil with permanent cover.
Maize residue cover, no-till practices

Elegible practices
Crop residue management: providing the soil with permanent cover.
Soybean growing on maize residues

Elegible practices
Crop residue management: providing the soil with permanent cover maize

Soils gaining organic carbon and increasing porosity, after the adtoption of SSM practices

Elegible practices
Use of cover crops or green manure, and/or perennials in crop rotations; establishing a pasture in croplands or bare fallow


Soils gaining organic carbon and increasing porosity, after the adtoption of SSM practices
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5 Stage 2: delineating boundaries

5.1 Spatial boundaries

The project 'spatial boundary' geographically delineates all lands where SSM practices are to be implemented. Target IA/IAs shall be identified, delineated and mapped such that:

a) all land included in the IA is eligible land (refer to Section 4.2) and is subject to the carrying out or maintenance of at least one eligible management practice until the end of the project duration. Non-contiguous parts of the project area are to be mapped as separate IAs.

b) the boundaries of the IA used in the baseline (year 0) sampling round (see Section 7) must be the same as the boundaries used in each subsequent sampling round.

c) the exact location and geospatial map of each IA is provided, including:

- boundaries or GPS tracks of the intervention areas limits (polygon vector type: KML or .SHP formats);
- Google Earth, Bing Aerial or satellite images indicating the project's different intervention areas and sizes (in hectares), labelling locations and areas within each IA to be excluded (for example, wet depressions, woodlots, forests, waterways, farm buildings);
- Google Earth, Bing Aerial, or satellite historic images providing evidence that the IAs are not located in lands that have been forests or wetlands/peatlands during the past ten years (see restricted lands, Section 4.2).

The World Geodetic System (WGS84) shall be used as the reference coordinate system in all cases.

5.2 Project location within global soil organic carbon sequestration map regions

As a reference, a geospatial capture clearly indicating the project location within the latest version of the national FAO-GSOC map (Global soil organic carbon map) and FAO-GSOCseq map (Global soil organic carbon sequestration potential map, when available) shall be included. Current SOC stock (t C/ha at 30 cm) and predicted annual sequestration rates (t C/ha/yr) by the FAO-GSOCseq map shall also be detailed.

5.3 Temporal boundaries

The project 'temporal boundary' refers to the total duration of the projected activities. The start date and end date of the implementation of SSM practices need to be defined for each IA. A minimum duration of eight consecutive years is required to capture enough data to demonstrate soil carbon sequestration compared to a baseline scenario and baseline period (or year 0), reducing uncertainties as much as possible.

6 Stage 3: Delineating the baseline (business as usual) and intervention scenarios

In order to perform a preliminary assessment on SOC sequestration and GHG emissions (Section 7), the baseline scenario must be appropriately identified. It shall be determined by identifying farm 'business as usual' (BAU) conditions:

a) the land use and management practices that were in place during the five years prior to the intervention.

b) regional 'business as usual' conditions: the land use and management practices that represent the typical land uses and agricultural management practices (prevailing practices) which are dominant within the larger intervention region (e.g. neighbouring areas with similar

soils and production systems) or specific intervention areas of the project, prior to the start of the interventions.

The identified practices to define the BAU scenario must be realistic and credible on the basis of verifiable information sources, such as national agricultural statistics reports, documented public management records of land users, published peer-reviewed studies in the project region, results of surveys conducted by or on behalf of the project proponent prior to the initiation of project activities.

A five-year baseline period is standardized as a reasonable timeframe prior to the implementation of SSM practices, in which activity data that can be used to define a BAU scenario is available, credible, and updated for most projects. Business-as-usual scenario definition is based on the provision of five-year historic activity data for the IAs to be assessed, including:

- cash and cover crops per year (approximate sowing and harvest dates), and harvested yields or biomass (kg DM/ha/yr);
- residue management; residue returns and removals estimation (percent or kg DM/ha/yr);
- forage type, estimated total biomass production (kg DM/ha/yr);
- and estimated consumption/harvest (percent or kg DM/ha/yr);
- livestock species, density (annual average stocking rate), categories (average weight), and general grazing management description;
- tillage practices (tillage system, number and type of tillage operations per year);
- annual mechanized farm operations (number) and fossil fuel consumed: tillage, planting, pest control, fertilizer/organic and inorganic amendments/manure application and distribution, harvesting, mowing, baling hay, internal transportation, other operations;
- fertilizer and inorganic amendment use (product, application method, moment/s of application, fertilizer and nutrient doses per year in kg/ha);
- organic amendment use (type, form of application, placement method, timing and application rate per year);
- irrigation management (type, water source, water quality parameters including electrical conductivity and sodium adsorption ratio, irrigation period, periodicity/frequency, total annual mm); irrigation annual fossil fuel consumption;
- agroforestry: number and species of trees used, projected or actual diameter at breast height (DBH) of trees.

Once the BAU scenario is characterized, the Intervention Scenario (IS) shall also be defined, based on activity data. The IS shall include at least one of the eligible practices included in Section 4.3. As in the case of the BAU scenario, the description of the IS scenario shall include activity data in the past five years, regarding the projection of the proposed SSM practices.

7 Stage 4: Preliminary assessment of soil organic carbon and greenhouse gas emissions

Before the implementation of SSM and resource-demanding monitoring activities, the project must demonstrate higher SOC sequestration without increasing overall (net) GHG emissions compared to a baseline (business as usual) scenario. If the new practices are an improvement over a specific baseline scenario, they are considered additional.

Additionality advances environmental integrity by ensuring that only projects that would not have happened anyway are eligible for carbon credits or carbon offsets. In practice, additionality can be assessed in a number of ways (Schneider *et al.*, 2017):

- Investment analysis: the activity is not economically viable without crediting (investment comparison analysis, benchmark analysis, simple cost analysis);
- Barrier analysis: an economically attractive activity faces prohibitive barriers of some other kind;
- Positive lists, negative lists, eligibility criteria and decision trees: these lists determine what type of activities are likely to be additional (or not).

Since this MRV is specific for agricultural practices from an agronomic point of view in order to assess additionality' these questions will be addressed (Thamo and Pannel, 2016):

- Is the sequestering practice additional?
- If so, what is the 'benchmark' farming practice that it would displace?
- How much of the GHGs abatement resulting from the new practice is additional?

7.1 Preliminary assessment: soil organic carbon modelling

Soil organic carbon stock (t C/ha) at 0-30 cm shall be projected for BAU and IS using SOC simulation models for a 20-year period, using historic and projected activity data collected in Stage 3 as inputs for the model. A minimum projection of 20 years is required in order to allow comparisons and harmonization of different projects and GHG accounting methods (IPCC, 2006, 2019).

The same SOC model must be used for all the stages of the MRV protocol. Evidence shall be provided (scientific journals, university theses, local research studies or work carried out by the project proponent) demonstrating that the use of the selected SOC model is appropriate for the agroecological zone where the project is located. A multi-model ensemble approach (e.g. Riggers *et al.*, 2019; Lehtonen *et al.*, 2020), using multiple models to make predictions of SOC stocks for each IA, is the preferred option, but SOC estimates can be performed using single models. No specific SOC model is prescribed in this protocol. However, this protocol provides a general standard methodology adapted for the use of RothC model (Coleman and Jenkinson, 1996), because of its widespread use, relative simplicity and fewer data requirements compared to other SOC models. As shown by FAO-LEAP Guidelines (FAO, 2019a), the adoption of other soil carbon models is also possible, as long as this model is adjusted for the geographic area and situation of the project. RothC model description, required activity data and estimations methods, and general modelling procedures to simulate SOC stocks for a 20-year period are described in Annex 1: Modelling sub-protocol.

At this stage, historic climatic records and soil data can be obtained from global data sources, but locally validated data is preferred (data sources must be indicated). Table A1 (Annex) illustrates the required data to perform a Preliminary additionality assessment using the RothC model.

Simulation results are used to estimate the magnitude of change in SOC sequestration per unit area (ΔSOC_{seq}) for each IA. Relative SOC sequestration is determined as the difference between projected SOC stocks after the defined period (20 years) for the Intervention Scenario and Business-As-Usual scenarios:

$$\Delta SOC_{seq}\,(t\,C\,ha^{-1}) = SOC_{IS} - SOC_{BAU}$$

Equation 7.1

where SOC_{IS} is the soil organic carbon stock at 0-30 cm depth under the intervention scenario, after 20 years of implementing land use/land cover and management practices; SOC_{BAU} is the soil organic carbon stock at 0-30 cm depth under the business-as-usual scenario, after the same period.

SOC sequestration rates per area unit shall be determined for each IA as the average yearly sequestration rates of the specified period (D, in years, where D=20):

$$SOC_{seq\ rate}\,(t\,C\,ha^{-1}yr^{-1}) = (SOC_{IS} - SOC_{BAU}) / D$$

Equation 7.2

Total Sequestration (in t C) and total Sequestration rate (t C/yr) of each IA shall be determined by multiplying its area by the

determined SOC sequestration per unit area. Total sequestration of the project is to be determined by summing the sequestered SOC (t C) estimated for the different IAs. At this stage, similar IAs with similar management practices can be grouped in order to perform joint estimations.

ΔSOC sequestration and sequestration rates can be expressed as CO_2 removals per unit area per unit time (R) as:

$$R\ (t\ CO_2 eq\ ha^{-1}) = \Delta SOC_{seq} * 44/12$$

Equation 7.3

Total removals (t CO_2eq) of each IA shall be determined by multiplying its area by the determined removals per unit area. Total project removals shall be determined by summing the estimates of the different IAs.

7.2 Preliminary assessment: projected greenhouse gas emissions

Annual agricultural key GHG emissions shall be estimated for a 20-year period following IPCC Guidelines (2006, 2019). Key GHG emission agricultural sources included in this protocol are:

a) N_2O emissions from agricultural soils (direct and indirect emissions from fertilizers, manures, crop residues, livestock grazing);

b) CH_4 emissions from enteric fermentation by livestock;

c) CH_4 and N_2O emissions from manure management in livestock farms;

d) CH_4 emissions from paddy soils;

e) CO_2 emissions by land use changes or land management when applicable, estimated by SOC modelling (Section 7.1).;

f) CO_2 emissions from fossil fuels (farm machinery and irrigation system);

g) CO_2 direct emissions from specific fertilizers (urea decomposition).

Required activity data, estimation methods, and general procedures to estimate GHG emissions for a 20-year period using IPCC methodology are described in Annex A2: Greenhouse gas emissions estimation tools sub-protocol. All emissions will be expressed in CO_2-equivalent units (CO_2eq). Total GHG emissions (t CO_2eq ha^{-1}) and emission rate (t CO_2eq ha^{-1} yr^{-1}) shall be estimated for the BAU and IS.

Net GHG emissions (t CO_2eq ha^{-1}) and emission rate (t CO_2eq ha^{-1} yr^{-1}) shall be estimated for the BAU and IS as the difference between emissions and removals due to SOC sequestration (Section 7.1, Equation 3):

$$Net\ GHG_{BAU}\ (tCO_2 eq.ha^{-1}) = GHG_{BAU} - R_{BAU}$$

Equation 7.4

$$Net\ GHG_{IS}\ (tCO_2 eq.ha^{-1}) = GHG_{IS} - R_{IS}$$

Equation 7.5

where GHG_{BAU} are the estimated emissions under the business-as-usual practices for a 20-year period; GHG_{IS} are the projected emissions after land use/cover and management practices are implemented; R_{BAU} are the projected CO_2 removals as SOC for the business as usual practices (estimated as explained in Section 7.3); and R_{IS} are the projected CO_2 removals as SOC after 20 years of implementing land use/cover and management practices (estimated as explained in Section 7.3).

To estimate additionality, change in Net GHG (ΔGHG_{Net}) emissions are determined for each IA as the difference between projected net emissions after the defined period of time (20 years) for the IS and BAU practices:

$$\Delta GHG_{Net}\ (t\ CO_2 eq\ ha^{-1}) = GHG_{IS} - GHG_{BAU}$$

Equation 7.6

8 Stage 5: Monitoring

The objective of the monitoring stage is to demonstrate periodically that the adopted SSM practices in the IS are capturing atmospheric CO_2 in the short term, sequestering C in soils in the medium term, and reducing GHG emissions with respect to a baseline scenario. The monitoring stage includes three combined monitoring activities to be undertaken during the project implementation: Soil sampling monitoring, SOC modelling monitoring and GHG estimates monitoring.

8.1 Soil sampling monitoring program: soil organic carbon stocks and optative particulate organic carbon contents

The soil sampling monitoring program is aimed at detecting soil organic carbon (SOC) concentration and stock changes from an initial baseline condition (stock at year 0), in order to demonstrate that the adopted SSM practices are either increasing or maintaining SOC stocks. Soil bulk density (BD) determinations are required to calculate SOC stocks (see Annex A5). As SOC changes may take longer than five or six years in many cases, this protocol also includes the periodic soil monitoring of labile fractions with high turnover rates, that are usually more sensitive to management practices.

SOC stabilization times are very long, as they are measured over several years. In the case of this MRV, sampling is proposed after four and eight years, with the idea of being able to capture the changes that can take place in many soils by implementing SSM practices. In order to detect these changes, it is not only necessary to allow a good number of years to pass, but also to carry out an adequate and sufficient sampling strategy to detect even small increases in SOC. This does not usually happen with the chemically labile or easily accessible fractions of SOC that cycle in less time, as is the case of Particulate Organic Carbon (POC) associated with partially decomposing plant residues.

Particulate organic carbon can be defined as the SOC content associated with little transformed crop residues, which can be obtained from the soil that is ground and sieved and which remains in 53–2000 µm screen opening sieves. This fraction includes partially decomposed organic residues (Haynes, 2005) and contains microbial biomass together with fresh plant residues and decomposing organic material (Gregorich *et al.*, 1994). Particulate organic carbon is thus biologically and chemically active and is part of the labile (easily decomposable) pool of soil organic carbon (SOC). Unlike SOC, POC usually changes in the first layer of the soil where decomposing waste is deposited. Although changes in POC does not necessarily indicate changes in SOC sequestration, it is used in this protocol as an indicator of changes in those SOC fractions more sensitive to management practices.

To monitor SOC stocks and POC contents and their changes over time at the specified time intervals within an IA, the following steps are required (detailed in their corresponding sub-protocols):

1) Sampling design: stratification, sample location, sample size and compositing shall be performed according to the soil sampling sub-protocol (Annex, A3).

2) Field sample collection: sampling frequencies, sampling depths, soil core extraction methods according to the methodologies described in the soil sampling sub-protocol (Annex, A3).

3) Sample preparation according to the soil sampling sub-protocol (Annex, A3).

4) Laboratory determinations: SOC and POC concentration, and BD, according to the procedures and methodologies described in the laboratory analysis sub-protocol (Annex, A5), following the standard operating procedure for soil organic carbon, Global Soil Laboratory Network (GLOSOLAN) procedures (FAO, 2019c).

5) Spectrometry and remote sensing methods (optative): Considering that soil sampling and laboratory determinations are costly and time-consuming, the use of spectrometry methods (see Annex 6) and remote sensing to estimate SOC stocks and concentrations can be also used, when technical capacities for adequate calibration are available. Due to

detrimental effects from soil moisture, soil roughness, vegetation cover, and others that affect SOC spectral response, these methods require adjustment to local conditions (Angelopoulou *et al.*, 2019, 2020). Evidence shall be provided (scientific journals, university theses, local research studies or work carried out by the project proponent), demonstrating that the use of these methodologies is appropriate for the agroecological zone and soil conditions were the project is located.

6) Calculation of SOC stocks according to SOC stock determination and stock changes sub-protocol (Annex, A4).

7) Calculation of the change in SOC over time within each IA, according to SOC stock determination and stock changes sub-protocol (Annex, A4).

The soil sampling rounds of this monitoring program can be summarized as:

a) Mandatory Baseline (Time = 0): complete sampling round including SOC concentration (0-10 cm and 10-30 cm soil depths; optative up to 1 m depth, distinguishing different soil layers, as appropriate); soil bulk density (same soil layers as SOC); and SOC stock estimations (0-30 cm, or sum of SOC stocks in the different layers).

b) Optative every two years: POC concentration (0-10 cm).

c) Mandatory every four years: complete sampling round including SOC concentration (0-10 cm and 10-30 cm soil depths; optative up to 1 m depth, distinguishing different soil layers, as appropriate); soil bulk density (same soil layers as SOC); and SOC stock estimations (0-30 cm, or sum of SOC stocks in the different layers).

8.2 Soil organic carbon modelling monitoring program

Model simulations of SOC stocks 0-30 cm (or optative up to 1 m depth) for a 20-year period shall be performed for the BAU and IS, every two years, using the same simulation model and procedures as in the preliminary additionality assessment (Section 7.1 and sub-protocol A1); however, at this stage measured and collected local data since the project implementation (e.g. monthly temperature/precipitation/evapotranspiration, baseline/initial measured SOC stocks, estimated carbon inputs) must be used for the simulations.

As explained in Section 7.1, no specific SOC model is prescribed in this protocol. Process-oriented, multicompartment SOC models, such as RothC, Century, DNDC, EPIC and models derived from them (Stockmann *et al.*, 2013, FAO, 2019a) have been dominant in efforts to simulate SOC changes in agricultural systems, but other models considered more appropriate according to the agroecological conditions can be used. Evidence shall be provided (scientific journals, university theses, local research studies or work carried out by the project proponent) demonstrating that the use of the selected SOC model is appropriate for the agroecological zone where the project is located. The same SOC model must be used for all the stages of the MRV protocol.

Required activity data, estimations methods, and general modelling procedures to simulate SOC stocks for a 20-year period using the RothC model as an example are described in Annex A1, Modelling sub-protocol. As explained in Section 7.1, simulation results are used to estimate relative SOC sequestration per unit area for each IA, using Equations 1 and 2, and CO_2 removals (Equation 3).

The modelling monitoring program can be summarized as follows:

a) Time = 0: Projected (20 years) total and annual SOC sequestration and CO_2 removals for the IS (as estimated in the preliminary assessment, Section 7.2), for each IA.

b) Every two years: Current (past monitoring period) and projected (20 years) total and annual SOC sequestration and CO_2 removals for the IS, for each IA, using collected activity data.

8.3 Greenhouse gas emissions monitoring program

Annual agricultural key GHG emissions shall be estimated for a 20-year period as defined in the IPCC Guidelines (2006, 2019).

For each IA, annual absolute and net GHG emissions estimates shall be performed using the same sources considered in the preliminary additionality assessment (Section 7.2), and the methodologies described in the corresponding Sub-protocol (Annex A2: Greenhouse gas emissions estimation tools sub-protocol); however, at this monitoring stage, measured and collected local data since the project implementation (e.g. synthetic fertilizer used doses, consumed fuel, crop residues, livestock stocking rates) must be used for the estimations.

This monitoring program can be summarized as follows:

a) Time = 0: Projected (20 years) total and annual GHG emissions for the BAU and IS (as estimated in the preliminary assessment, Section 7.2), for each IA.

b) Every two years (optional): Current (past monitoring period) and projected (20 years) total GHG and annual emissions for the BAU and IS, for each IA, using collected activity data.

c) Every four years: Current (past monitoring period) and projected (20 years) total GHG emissions for the BAU and IS, for each IA; plus CO_2-equivalent (CO_2eq) emissions/removals budget (Net emissions) estimated from measured (Section 8.1) and modelled SOC stock changes (Section 8.2) and estimated CO_2eq agricultural GHG emissions (this section).

Required activity data, methods, and general procedures to estimate GHG emissions for a 20-year period using IPCC Guidelines are described in Annex A2: Greenhouse gas emissions estimation tools sub-protocol. As explained in Section 7, all emissions will be expressed in CO_2-equivalent units (CO_2eq).

Activities, determinations and estimations of the three monitoring programs (Sections 8.1 to 8.3) are summarized in Table 1.

Table 1 | Activities, determinations and estimations of the soil sampling, modelling and GHG monitoring programs.

Time	Activity	Determinations and Estimations
Time = 0	Projected soil management (Activity Data)	Tillage, crop types and rotations, fertilizer plans, manure, etc.
	Baseline complete soil sampling round	Particulate Organic Carbon concentration (0-10 cm) (optative)
		Soil Organic Carbon concentration (0-10 cm and 10-30 cm; optative up to 1 m depth)
		Soil bulk density (same soil layers as Soil Organic Carbon sampling)
		SOC Stocks (0-30 cm; optative up to 1 m depth)
	SOC modelling (20 yr)	Projected SOC stocks (IS and BAU) (from baseline SOC)
		Projected total (20 yr) and annual SOC sequestration (IS)
		Projected total (20 yr) and annual CO_2 Removals (IS)
	Estimated GHG emissions (20 yr)	Projected total (20 yr) and annual GHG emissions (CO_2eq) from key agricultural sources
Every 2 yr	Performed and Projected soil management (Activity Data)	Tillage, crop types and rotations, fertilizer plans, manure, etc.
	Periodic soil sampling round	Particulate Organic Carbon (0-10 cm) (optative)
	SOC modelling (20 yr)	Current and Projected SOC stocks (IS and BAU)
		Current and Projected total (20 yr) and annual SOC sequestration (IS)
		Current and Projected total (20 yr) and annual CO2 Removals (IS)
	Estimated GHG emissions (20 yr)	Current and Projected total (20 yr) and annual GHG emissions (CO2eq) from key agricultural sources
Every 4 yr	Performed and Projected soil management (Activity Data)	tillage, crop types and rotations, fertilizer plans, manure, etc.
	Periodic complete soil sampling round	Particulate Organic Carbon concentration (0-10 cm) (optative)
		Soil Organic Carbon concentration (0-10 cm and 10-30 cm; optative up to 1 m depth)
		Soil bulk density (same soil layers as Soil Organic Carbon sampling)
		SOC Stocks (0-30 cm; optative up to 1 m depth)
	SOC modelling (20yr)	Current and Projected SOC stocks (IS and BAU)
		Current and Projected total (20 yr) and annual SOC sequestration (IS)
		Current and Projected total (20 yr) and annual CO_2 Removals (IS)
	Estimated GHG emissions (20 yr)	Current and Projected total (20 yr) and annual GHG emissions (CO_2eq) from key agricultural sources
	CO_2eq absorptions/emissions budget	Current and Projected CO_2eq budget (Emissions - Removals)


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Monitoring SOC stocks.
Soil sampling up to 0-30 cm depth to determine SOC concentration, in a no-till field

Monitoring SOC stocks.
Soil sampling up to 1 m depth to determine SOC concentrations in a no-till field

Monitoring SOC stocks.
Soil sampling to determine SOC concentration at 0-10 and 10-30 cm depths, with an auger, in a no-till wheat-soybean-maize rotation

Inspecting for healthy roots after the adoption of SSM practices in a soybean field

Monitoring SOC stocks.
Soil sampling to determine SOC concentration: 0-30 cm depth with an auger

Monitoring SOC stocks.
Soil sampling:up to 1 m depth with an auger, in a no-till rapeseed-soybean-maize rotation

Monitoring SOC stocks. Soil bulk density measurements.
Soil bulk density sampling, undisturbed (intact) core method

Monitoring SOC stocks.
Soil bulk density measurements.
Soil bulk density sampling, core method,
using a rubber mallet

Monitoring of SSM practices. Combining SOC measurements with other soil indicators, as water infiltration

Soils gaining organic carbon after the adtoption of SSM practices

Healthy soybean roots in soils gaining organic carbon after the adtoption of SSM practices

Assessing soil structure after the adoption of SSM practices


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9 Stage 6: Reporting and verification

The objective of the reporting stage is to make the information accessible to a range of users and facilitate public disclosure and periodic verification of the information provided. The project stakeholder/s must report the degree to which they have been able to achieve the emissions reductions, by compiling it in inventories and standardized formats, to be then verified by an independent, third-party auditor.

All stages of the MRV require the presentation of reports in certain formats. Many of these formats or templates already exist in the world and are available on the Web, such as those proposed by the Certified Carbon Standard (VCS-VERRA, 2019) for the VCS Program (https://verra.org/project/vcs-program/).

Four types of reports are necessary to comply with this MRV protocol (Figure 1):

a) Pre-implementation report;

b) Initial report;

c) Bi-annual reports;

d) Final reports.

9.1 Pre-implementation report (project description)

This report must include a project description:

- Spatial boundaries: the exact location and geospatial map as described in Section 5.1; location within the FAO-GSOC and FAO-GSOCseq maps (see Section 5.2); satellite historic images providing evidence that the IAs are not located in lands that have been forests or wetlands/peatlands during the past ten years (see restricted lands, Section 4.2).
- Temporal boundaries: project duration.
- Records and results of the business as usual (BAU) management delineation: summary of the historic activity data for the different fields to be assessed (e.g. areas, crops, yields, tillage practices, fertilizer use, organic amendment use, livestock density; detailed in Section 6).
- Records and results of the Intervention Scenario (IS) delineation: IAs spatial boundaries and identification, description of proposed SSM practices; summary of the projected activity data regarding the implementation of SSM practices (Section 6).
- Expected risks of reversals and leakages, and proposed activities to reduce risks.
- Results of the preliminary additionality assessment:
    - Modelled SOC stocks for the BAU and IS, SOC sequestration (IS-BAU), SOC sequestration rates, projected CO_2 removals; per area unit (ha), for each IA, and for the whole project.
    - Total and Net GHG emissions estimations for the BAU and IS; relative GHG emissions (IS-BAU); per area unit (ha), for each IA, and for the whole project.
- Soil sampling plan (see Annex A3).

9.2 Monitoring report

9.2.1 Initial report

This report must include the following:

- Implementation status of the projected activities and deviations;
- Baseline SOC stocks: initial sampling round results (SOC and POC concentration and bulk density), laboratory reports, measured depths, sample locations (latitude and longitude), SOC stock estimations (per area unit, for each IA and for the whole project);
- Results of the modelling and GHG monitoring programs using measured and collected activity data:

- Modelled SOC stocks for the BAU and IS, SOC sequestration (IS-BAU), SOC sequestration rates, projected CO_2 removals; per area unit (ha), for each IA, and for the whole project.
- Total and Net GHG emissions estimations for the BAU and IS; relative GHG emissions (IS-BAU); per area unit (ha), for each IA, and for the whole project.

9.2.2 Biannual reports and final report

These reports must include the following:

- Implementation status of the projected activities and deviations, since the beginning of the project;
- Evidence that projected SSM practices are being implemented shall be provided in annex sections:
  - digital imagery and/or remote sensing indices (e.g. normalized difference vegetation index - NDVI) that provide evidence of the monthly and annual evolution of the vegetation cover for each IA, indicating date and source of the satellite images;
  - relevant invoices, receipts, contractual arrangements and/or sales records;
- Reversals that exceed 10 percent of the area;
- SOC stock changes from Soil Monitoring Program: sampling round results (SOC and POC concentration and bulk density), laboratory reports, measured depths, sample locations (latitude and longitude), SOC stock estimations (per area unit, for each IA and for the whole project); SOC stock changes every four years and POC concentration changes every two years since the beginning of the project;
- Results of the modelling and GHG monitoring programs using local activity data:
  - Current and projected SOC stocks for the BAU and IS, SOC sequestration (IS-BAU), SOC sequestration rates, projected CO_2 removals; per area unit (ha), for each IA, and for the whole project; since the beginning of the project.
  - Current and projected Total and Net GHG emissions estimations for the BAU and IS; relative GHG emissions (IS-BAU); per area unit (ha), for each IA, and for the whole project; since the beginning of the project.

9.3 Accredited professional responsibilities

All reports (initial and monitoring reports) must be submitted with the signature of a professional in the sustainable management of agricultural soils or related fields, accredited by FAO participating national institutions in the project, certifying the accuracy of the information provided and attaching a brief CV which shows the experience of the professional. The required experience can be academic and/or professional.

9.4 Verification

Verification refers to the process of independently checking the accuracy and reliability of reported information or the procedures used to generate that information. By providing feedback on measurement/monitoring methods and procedures and improvements in reporting, verification also provides quality assurance and quality control that improves this MRV (see RECSOIL Market Place Chapter, C *d iv* Section).

As previously stated, verification is a process that must be conducted independently of monitoring and reporting processes. Other people and/or companies will be responsible for verification, as with QA/QC processes described in IPCC Guidelines (IPCC, 2006a).

Verification is achieved in this MRV by periodically subjecting the reports to external reviewers accredited by FAO, in order to establish completeness and reliability. Verification helps to ensure accuracy and conformance with any established procedures, and to provide meaningful feedback for future improvement.


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10 References (including Annexes)

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Glossary

Activity data: Data on the magnitude of a human activity resulting in emissions or removals taking place during a given period. Data on energy use, land areas, management systems, lime and fertilizer use are examples of activity data.

Additionality: An action is deemed additional if it leads to lower levels of emissions than would have otherwise occurred under business as usual.

Baseline scenario: The land use and management practices that were in place prior to the intervention. The baseline (or reference) is the state against which change is measured. In the context of transformation pathways, the term 'baseline scenarios' refers to scenarios that assume that
no mitigation policies or measures
will be implemented beyond those that
are already in force and/or are legislated or planned to be adopted.
In much of the literature the term is also synonymous with the term 'business-as-usual (BAU) scenario'.

Baseline SOC stocks: The initial soil organic carbon (SOC) stocks at the beginning of the monitoring period (year = 0).

Carbon sequestration: The rate of increase in long-term storage of soil organic carbon (SOC).

Composite sample: A sample in which the sampling units are pooled together and homogenized.

Dissolved organic carbon: it represents a general description of the organic carbon dissolved in water. Operationally, it can be defined as the fraction of organic carbon that can pass through a 0.45 µm filter filter pore size.

Intervention area: The area, composed of strata, for which soil organic carbon stocks will be estimated.

Intervention scenario: The land use and sum of Sustainable Soil Management practices that are going to be implemented.

Leakage: Indirect greenhouse gases emissions or soil organic carbon losses that can occur outside the project's boundaries but are still attributable to the project's activities.

Measuring SOC: Is the process of quantifying soil organic carbon contents restricted to the fraction < 2mm in size, by direct sampling of soils and chemical analysis of carbon concentrations.

Minimal detectable difference: it refers to the smallest difference, or change, that can be statistically detected in a given study.

Monitoring: The process of collecting data, following and analyzing information over time and in space and overall implementation progress, with the purpose of providing information for reports.

Particulate organic carbon: Soil organic carbon without mineral interaction, constituted commonly by vegetal residues fragmented and/or partially decomposed as determined by the fractionation method of Cambardella and Elliot (1993).

Permanence: Period of time in which a specific carbon pool is stored.

Preliminary assessment: Assessment performed before the implementation of Sustainable Soil Management practices, to demonstrate that the project has higher SOC sequestration than a baseline scenario, without increasing overall GHG emissions.

Removals: The withdrawal of GHGs from the atmosphere, as a result of deliberate human activities. In this MRV, it refers to the withdrawal of CO_2 and its storage in soils as soil organic carbon.

Reporting: The delivery of monitoring results. Reporting should be done in a transparent manner and sharing information on the MRV's project impacts. Also the reporting shall provide background data, data sources and methodologies applied for data quantification and modelling.

Reversals: Re-emission of sequestered SOC.

Sample: Individual soil cores taken in the field.

Soil carbon: Soil carbon (C) refers to the solid terrestrial matter stored in global soils. This includes both the organic and inorganic carbon in soil. Organic C as organic matter and inorganic C as carbonates and bicarbonates minerals.

Soil organic carbon concentration: The amount of organic carbon in a soil sample relative to the total mineral content of the sample. Soil organic carbon content is expressed as a (mass) percentage, restricted to the fraction <2 mm in size.

Soil organic carbon stocks: The content or mass of organic carbon in a sample of known bulk density. Soil organic carbon stocks are expressed in tonnes or Mg C per hectare for a nominated depth and restricted to the fraction <2 mm in size.

Sustainable Soil Management: Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity.

Strata: The areas in which an intervention area is divided as a result from the stratification process.

Stratification: The division of a population into parts known as strata, particularly for the purpose of accounting for variation for a drawn sample.

Verifying: The systematic, independent and documented process in which the methodological consistency of the actions proposed is evaluated.

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Annex 1 Modelling sub-protocol

A1.1 The RothC model

RothC is a model for the turnover of organic carbon in non-waterlogged topsoils that allows for the inclusion of the effects of soil type, temperature, moisture content and plant cover on the turnover process, with a monthly time step (Coleman and Jenkinson, 1996). RothC is purely concerned with soil processes, and as such is not linked to a plant production model in its original version (the user shall define carbon inputs to the soil). SOC is split into four active compartments and a small amount of inert organic matter (IOM). Active compartments differ in the mean residence time of organic carbon in the soil. The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). The IOM compartment is resistant to decomposition and is calculated using the equation below (Falloon *et al.*, 1998):

$$IOM = 0.049 * SOC^{1.139}$$

Equation A1.1

where SOC is soil organic carbon, t C ha^{-1}

IOM is Inert organic matter, t C ha^{-1}

The structure of the model is shown in Figure A1.

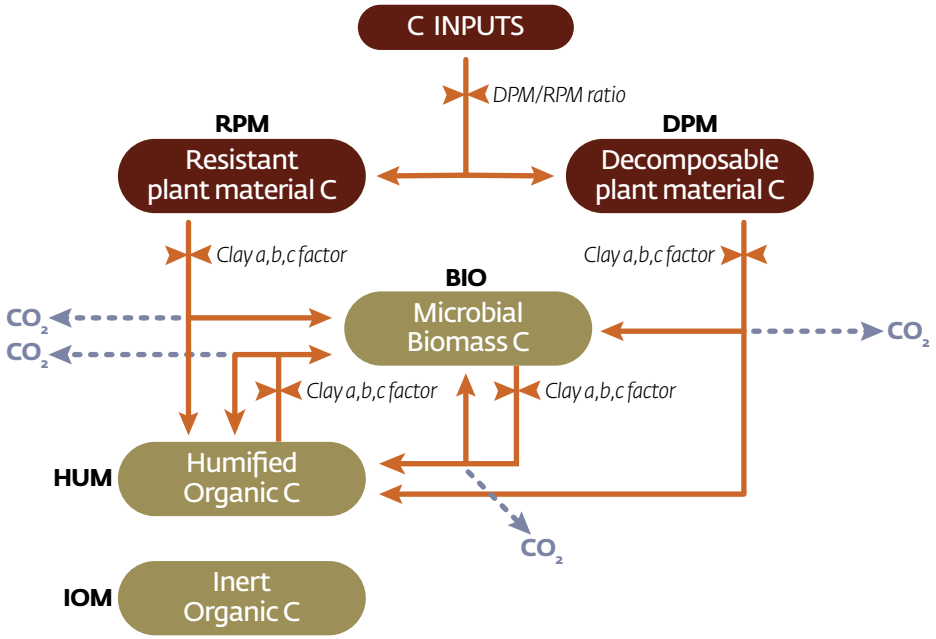


Figure A1 | Structure, pools, and flows of Carbon in RothC model, including major factors controlling the fluxes (a = multiplier for effects of temperature, b = multiplier for effects of moisture, c = multiplier for effects of soil cover; DPM/RPM = Decomposable/resistant plant material ratio). Redrawn from Falloon and Smith (2009)

Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. All incoming plant material passes through these two compartments once only. For most agricultural crops and improved grassland, DPM/RPM ratio is 1.44, i.e. 59% of the plant material is DPM and 41% is RPM. For unimproved grassland and scrub (including Savanna) a ratio of 0.67 is used. For a deciduous or tropical woodland a DPM/RPM ratio of 0.25 is used, so 20% is DPM and 80% is RPM.

Both DPM and RPM decompose to form CO_2, BIO and HUM. The proportion that goes to CO_2 and to BIO + HUM is determined by the clay content of the soil. The BIO + HUM is then split into 46% BIO and 54% HUM. BIO and HUM both decompose to form more CO_2, BIO and HUM. Each compartment decomposes by a first-order process with its own characteristic rate. If an active compartment contains Y t C/ha, this declines at the end of the month to:

$Y\ e^{-abckt}\ t\ C\ ha^{-1}$

Equation A1.2

where a is the rate-modifying factor for temperature; b is the rate-modifying factor for moisture; c is the soil cover rate-modifying factor; k is the decomposition rate constant for that compartment; and t is 1/12, since k is based on an annual decomposition rate. Y (1 - e^{-abckt}) is the amount of the material in a compartment that decomposes in a particular month.

RothC has also been adapted to simulate N and S dynamics (Falloon and Smith, 2009), but nutrient and C dynamics are not interconnected in RothC. It was originally developed and parameterized to model the turnover of organic C in arable topsoils, and it was later extended to model turnover in grasslands, savannas and woodlands, and to operate in different soils and under different climates (Coleman and Jenkinson, 1996).

A1.2 RothC required activity data

A1.2.1 Climate data

Historic climatic records (10 years previous to the project implementation) shall be obtained from one or more meteorological station/s from research institutions, extension offices or other public institutions, whose meteorological coverage can be shown to be applicable to the project area. Required climatic data to run the RothC model include:

- **Average Monthly rainfall (mm)** (plus monthly irrigation, in mm);
- **Average monthly mean air temperature (ºC);**
- **Average Monthly open pan evaporation** (mm)/ potential evapotranspiration (mm). Monthly evapotranspiration data (ET) needs to be converted to pan evaporation (Epan = ET/0.75). If no evapotranspiration data are available, ET may be estimated from temperature, solar radiation or other climatic variables (Hargreaves and Samani, 1985; Droogers and Allen, 2002).

For the preliminary assessment, historic climatic records can be obtained from global data sources (See table A1, Annex), but locally validated data is preferred. During the monitoring program, current temperature, precipitation, and evaporation monthly data obtained from neighbouring meteorological stations shall be used.

A1.2.2 Soil data

- **Soil texture** – Available clay content (%) measurements at 0-30 cm depth (particle size distribution, as determined by the pipette method (Day, 1965) or Bouyoucos method (1962) for each proposed intervention area, is the preferred option. However, for the preliminary assessment, clay contents can be acquired from national or global data sets (Table A1), and do not need to be measured at this stage by the project proponent. For the monitoring stage, clay content (%) measurements at 0-30 cm depth are needed.
- **Bulk density** - Needed to calculate initial SOC stocks, and equivalent soil mass corrections where necessary (see Annex A4, SOC stock calculation subprotocol).
- **Initial SOC stocks** – Available, recent (no more than 5 years prior to the implementation of the project) SOC concentration and stock estimations (t C ha^{-1}) at 0-30 cm depth (see methods, Annex, subprotocols A3-A4), for each proposed intervention area, are the preferred option. However, for the preliminary assessment, initial SOC contents can be estimated by running the model to equilibrium under constant environmental conditions and historic Carbon inputs of the BAU scenario. This procedure is further described in Section A1.3, General modelling procedures of this annex. Initial SOC estimates should be contrasted with the latest available version of the GSOC map (FAO-ITPS, 2019) to detect major deviations and to determine if the model estimated SOC equilibrium values are reasonable. At the monitoring program stage, measured initial SOC stocks need to be used as input for the model.

A1.2.3 Management data

Carbon inputs. Carbon inputs from various sources shall be preliminarily estimated from the activity data (crops, yields, residue removals, forage production, livestock units, manure/organic amendment application) provided for the BAU and IS. For the preliminary assessment, historic and projected activity data are to be used. For monitoring stage, current yields, forage production, stocking rates, and applied manure are to be used to estimate current C inputs (Ci).

Although the actual amount of Ci is difficult to assess, absolute and relative differences in Ci between BAU and IS can be estimated taking into account the framework proposed by Bolinder *et al.* (2007). According to this framework, net primary production can be expressed as the sum of four fractions:

$$NPP = CP + CS + CR + CE$$

Equation A1.3

where CP plant C in the agricultural product, the plant portion of primary economic value, and typically harvested and exported from the ecosystem. The 'product' can be either above ground (e.g., grain, hay or all exported/grazed aboveground plant material) or below ground (e.g., tuber). CS plant C in straw, stover/stubble and other aboveground postharvest residue. This fraction includes all aboveground plant materials excluding the 'product'. CR plant C in root tissue is composed of all belowground, physically recoverable plant materials, excluding any 'product'. CE plant C in extra-root material, including root exudates and other material derived from root-turnover, is not easily recovered by physically collecting or sieving. This fraction is roughly equivalent to what is sometimes referred to as 'rhizodeposition'.

Thus, total C input can be estimated as the sum of the C input of all plant fractions except the agricultural product:

$$Ci = CS + CR + CE$$

Equation A1.4

The amount of C in each of these fractions can be estimated from known agricultural yields, using published or assumed values for harvest index (HI), root to shoot ratios, plant C in root exudates, and C concentrations in residues. This protocol assumes the C concentration of all plant parts is 0.45 g C/g dry matter.

Carbon inputs in annual crops and annual forages: CP, CS, CR, and CE shall be estimated as:

$$CP = Yp \times 0.45$$

Equation A1.5

$$AB = Yp/HI$$

Equation. A1.6

$$CS = (AB - Yp) \times Ss \times 0.45$$

Equation A1.7

$$CR = ((Yp/HI) \times R{:}S) \times 0.45$$

Equation A1.8

$$CE = CR \times YE$$

Equation A1.9

where Yp is the dry matter yield or harvested aboveground biomass (t ha^{-1} yr^{-1}), AB is the aboveground biomass (dry matter, t ha^{-1} yr^{-1}), HI is the harvest index (harvested yield dry matter/ total aboveground dry matter). In the case of cover crops, Yp is considered to be 0, and hence, all aboveground dry matter is considered CS.

R:S is the root to shoot ratio (belowground biomass / aboveground biomass). The factor Ss (0-1) represents the faction from the aerial crop residues that remain in the field and are not removed (by default = 1). If a portion of the residues is removed (e.g., wheat straw removed for feed or bedding), then Ss < 1. Ye is the extra-root C (rhizodeposits) expressed as a factor relative to recoverable roots.

Whenever possible, locally validated estimations of HI and R:S and information shall be used, providing the information source. Other examples of shoot:root ratios and C contents in roots and shoots in different species can be found in Amanullah and Stewart (2013), Amanullah (2014), and Amanullah, Stewart and Hidayatullah (2015) and Amanullah, Stewart, and Amanullah *et al*. (2016).

Global estimates of HI and R:S provided in the IPCC Guidelines (2006; 2019) are to be used in the absence of locally validated information.

CE can be assumed to be ~ 65% of root biomass for annual crops and forages (CE = CR x 0.65) (Bolinder *et al.*, 2007).

Monthly carbon inputs of annual crops or forages can be obtained by dividing annual Ci into the different harvest events.

Carbon inputs in perennial crops and forages

$$CP = AB \times HI \times 0.45$$

Equation A1.10

$$CS = AB - (AB \times HI) \times Ss \times 0.45$$

Equation A1.11

$$CR = (AB \times R{:}S) \times 0.45$$

Equation A1.12

to be fully considered only when the perennial is discontinued

$$CE = CR \times Ye, \text{ to be yearly considered}$$

Equation A1.13

where AB is the total aboveground biomass production (dry matter, t $ha^{-1}yr^{-1}$), HI is the harvest index (harvested product, harvested forage or grazed biomass /total above ground dry matter), R:S is the root to shoot ratio. In the case of perennials, the factor Ss represents the fraction (0-1) of the remaining standing biomass that is returned to the soil as litter fall and/or harvest losses. For perennial crops, root C persists from year to year, so CR is defined as the increase in root C in the year it was established and is to be fully considered only when the perennial is discontinued (Bolinder *et al.*, 2007). CE represents rhizodeposits plus annual root turnover for perennials.

Whenever possible, ABP activity data and locally validated estimations of HI and R:S information shall be used, providing the information source. HI highly depends on the harvest or grazing efficiency of the productive system (usually between 0.5-0.8). Global estimates of HI and R:S for different perennial forages provided in the IPCC Guidelines (2006; 2019) are to be used in the absence of locally validated information. Approximately 50% of the remaining standing biomass can be considered as litter fall (Ss =0.5) and root turnover can be assumed to be ~ 50 % of root biomass (CE = CR x 0.5) (Poeplau, 2016).

Monthly carbon inputs of perennial crops or forages can be obtained by dividing annual Ci based on the estimated monthly biomass production, monthly vegetation cover, or equally dividing annual Ci across the growing season.

Carbon inputs from manure and organic amendments

Depending on the available data, C inputs from grazing animal faeces can be estimated either by:

Considering the fraction and digestibility of the consumed forage (Liu *et al.*, 2011):

$$Ci\ M\ (tC\ ha^{-1}\ yr^{-1}) = (AB \times HI) \times (1- D) \times 0.4$$

Equation A1.14

where AB is the total aboveground biomass production (dry matter, t ha^{-1} yr^{-1}), HI is the harvest index/efficiency (fraction of grazed biomass /total above ground dry matter), D is the digestibility of the consumed biomass (e.g. 40-70%), and 0.4 is the default C concentration in faeces.

Considering cattle type and weight, daily consumption, the digestibility of the consumed forage, and livestock units (IPCC, 2019):

$$Ci\ M\ (t\ C\ ha^{-1}yr^{-1}) = DMI\ (dry\ matter\ intake\ ,\ \%\ weight\ day^{-1}) \times W\ (kg\ head^{-1}) \times LU\ (heads\ ha^{-1}) \times (1- D) \times Days \times 0.4$$

Equation A1.15

where DMI corresponds to the daily dry matter intake (e.g. as a % of body weight), W the body weight of a specific category, LU the livestock units, D is the digestibility of the consumed dry matter (e.g. 40-70%), and 0.4 is the default C concentration in faeces.

Carbon inputs from livestock depositions can be estimated considering the above-mentioned options. Carbon inputs from applied manure (solid and liquid/slurry) should be estimated considering the dry matter concentration, and organic matter and carbon concentration of the applied product, which can be extremely variable depending on factors such as source, product, composting method, management, and storage.

Vegetation cover - For the preliminary assessment, knowledge of the historic and projected land use system is needed to determine months with or without vegetation cover. Historic vegetation cover (last 5 years) for a specific intervention area may be derived from NDVI (normalized vegetation index) evolution along the year. For the monitoring stage, information regarding current monthly vegetation cover (fallow vs vegetated) or NDVI evolution assessments shall be used.

DPM/RPM ratio - An estimate of the decomposability of the incoming plant material.

A1.3 General procedure

The model shall be able to simulate yearly SOC stocks (in t C ha^{-1} at 0-30 cm depth) under the BAU and IS, for a minimum of 20 years, using the above-mentioned activity data. Model results are highly sensitive to SOC initial stocks and C inputs estimates. Thus, prior to the 20 years 'forward' simulation, model initialization is required. Initialization refers to setting the initial SOC condition (total SOC and SOC of the different pools) at the start of the period over which stocks will be estimated so that further simulated results are a realistic estimate.

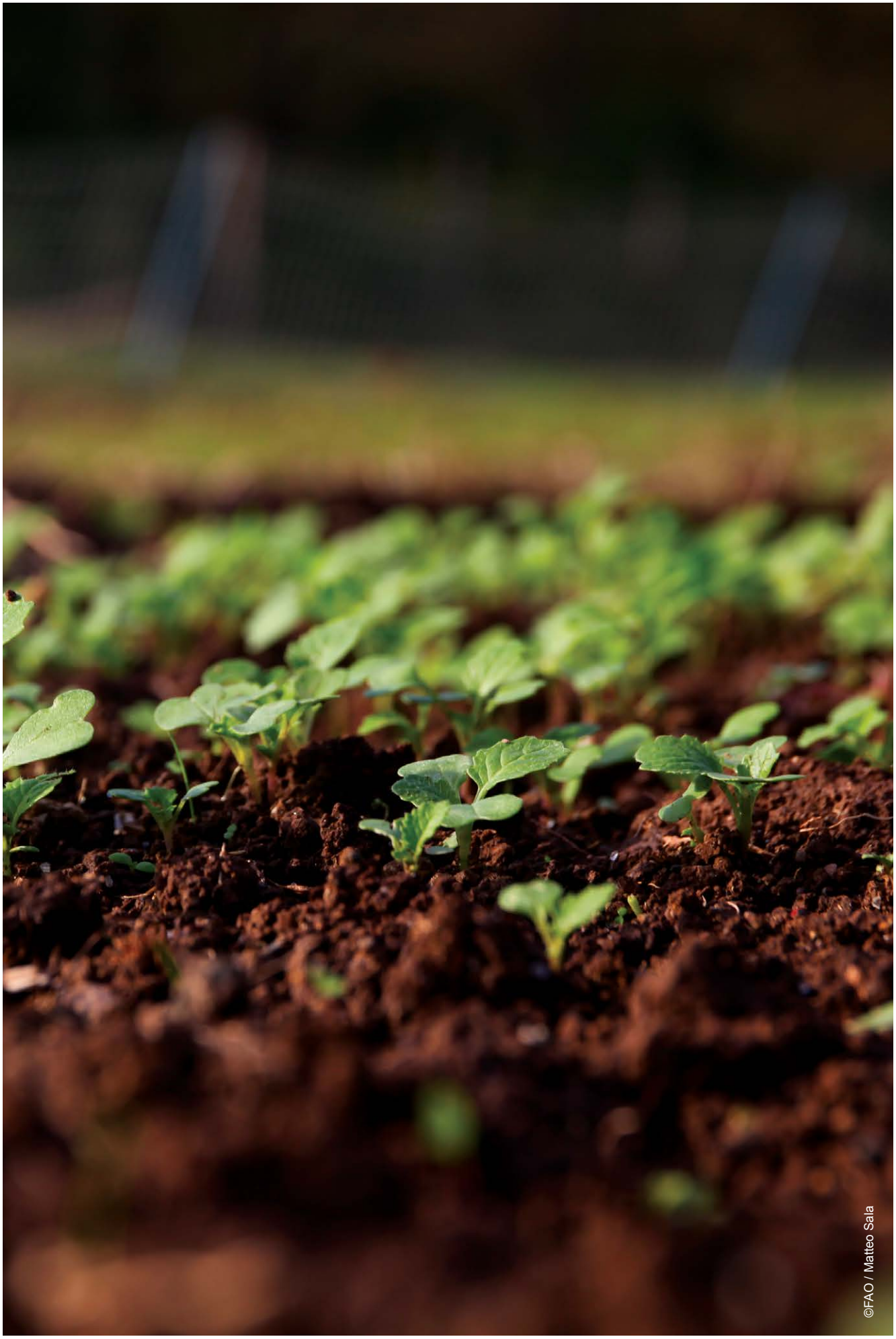
Initialization can be done using 'spin-up' / 'inverse mode' procedures to estimate the initial pool sizes:

- If the initial SOC is not known (e.g. when conducting preliminary assessments), the preferred option is to have the model estimate the initial SOC. In this case, an initialization 'spin-up' simulation period is required (10 000 years – conducted in 4 analytical steps), using the average estimated C inputs of the BAU scenario and average historic climatic data (last 10 years) as inputs. The estimated C input (See section above) will be critical to determining the modelled SOC amount. The modelled situation for the spin-up period is that representing the baseline condition.
- If the initial SOC stocks are known (e.g. *monitoring program*), a similar initialization 'spin-up' simulation (10 000 years–; phase 1) can be performed using the average estimated C inputs of the BAU scenario and average historic climatic data (last 10 years) as inputs. Then a short 'spin up' simulation of 10-20 years (phase 2) can be performed, using pool ratios estimated from the long spin up, yearly historic climate data and known C input historic data. C-input of the long spin up simulation (phase 1) can be adjusted so that modelled SOC matches measured SOC (<0.0001 t C ha^{-1}) at the end of both spin-up procedures (phase 1+2).

Following the model initialization, soil organic carbon stocks (t C ha^{-1}) are to be projected for a minimum 20 years period, for both the BAU and IS, considering the estimated or measured initial C stocks, average climate records, and estimated average C-input for each scenario. SOC sequestration (gain or loss) is thus determined as expressed in Equation 1.

Table A1 | Global Data Sources of Information

Type	Source	Address	Resolution
Monthly climatic data	CRU – Climate Research Unit, University of East Anglia	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.03/cruts.1905011326.v4.03/	50 km x 50 km
SOC stocks 0-30 cm	GSOC Map - FAO-ITPS	http://54.229.242.119/GSOCmap/	1 x 1 km
SOC stocks and SOC concentration; profiles	International Soil Carbon Network	https://iscn.fluxdata.org/	Different resolutions
Soil texture 0-30 cm	ISRIC Soil Grids	https://soilgrids.org and at global level from https://data.isric.org/)):	250 x 250 m 500 x 500 m 1 x 1 km
NDVI- Historic images (2001-2020) every 16 days	MODIS - MOD13A2 datasets	https://lpdaac.usgs.gov/products/mod13a2v006/	1 x 1km
Land Cover – Land Use	MODIS Land Cover Dynamics MCD12Q2	https://modis.gsfc.nasa.gov/data/dataprod/mod12.php	500 x 500m 1 x 1 km
Land Cover – Land Use	European Space Agency (ESA) Climate Change Initiative (CCI)- Copernicus Climate Change Service (C3S)	https://www.esa-landcover-cci.org/	300 x 300m
Land Cover – Land Use	IMAGE Integrated Model to Assess the Global Environment. PBL Netherlands Environmental Assessment Agency	https://models.pbl.nl/image/index.php/Land_cover_and_land_use	10 x 10 km
Land Cover – Land Use	FAO. Global Land Cover SHARE	http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1036355/	1 x 1km
Land Cover – Land Use	Land Use Harmonization Project	http://luh.umd.edu/index.shtml	~ 25 x 25 km
Land Cover – Land Use	USGS Global Land Survey	https://lta.cr.usgs.gov/GLS	30 x 30m
Land Cover – Land Use	CORINE land cover (Europe only)	https://land.copernicus.eu/pan-european/corine-land-cover	100 x 100 m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Annex 2 Greenhouse gas emissions estimation tools sub-protocol

Annual GHG emissions in agricultural soils are derived from the IPCC Guidelines for National Greenhouse Gas Inventories for the Agriculture, Forestry and Other Land Use (AFOLU) sector (IPCC, 2006, 2019), for croplands and grasslands categories.

Guidance and methods for estimating key GHG emissions and removals include:

a) N_2O emissions from agricultural soils (direct and indirect emissions from fertilizers, manures, crop residues, livestock grazing);

b) CH_4 emissions from enteric fermentation by livestock;

c) CH_4 emissions from manure management in livestock farms;

d) CH_4 emissions from paddy soils;

e) CO_2 emissions by land use changes or land management when applicable, estimated by SOC modelling (Section 7.1);

f) CO_2 emissions from fossil fuels (farm machinery and irrigation system);

g) CO_2 direct emissions from specific fertilizers (urea decomposition).

Emissions from livestock manure management are not included in this Guidance and methods, because they are considered not directly influencing GHG emissions and removals from soils.

A2.1 Greenhouse gases in the agriculture, forestry and land use sector

The key GHGs of concern are CO_2, N_2O and CH_4. CO_2 fluxes between the atmosphere and ecosystems are primarily controlled by uptake through plant photosynthesis and releases via respiration, decomposition and combustion of organic matter. N_2O is primarily emitted from ecosystems as a by-product of nitrification an denitrification, while CH_4 is emitted through methanogenesis under anaerobic conditions in soils and manure storage, through enteric fermentation, and during incomplete combustion while burning organic materials. Other gases of interest (from combustion and from soils) are NO_x, NH_3, NMVOCs (Non-methane volatile organic compounds) and CO, because they are precursors for the formation of GHGs in the atmosphere. Formation of GHGs from precursor gases is considered an indirect emission. Indirect emissions are also associated with leaching or runoff of nitrogen compounds, particularly NO_3 losses from soils, some of which can be subsequently converted to N_2O through denitrification. Figure A2.1 shows an idealized scheme with all gases emitted and removed from agricultural systems.

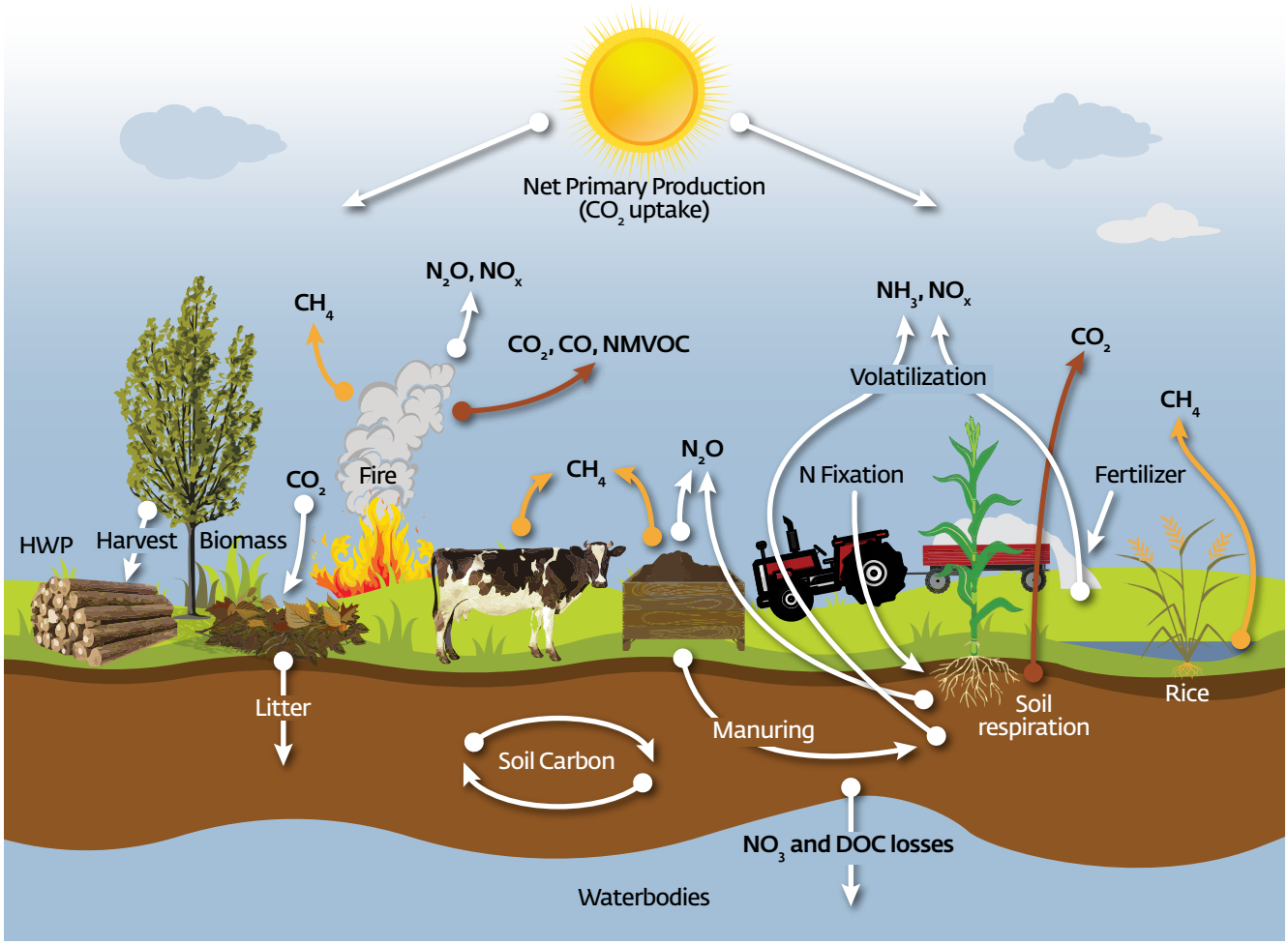

Figure A2.1 | Main sources of emissions and removals of greenhouse and trace gases in managed ecosystems (adapted from IPCC, 2006).

The following sections provide the methodologies to estimate these key GHG emissions. For the measurement of GHGs, affordable standard methods and appropriate guidelines should be followed (e.g. Khalil *et al.*, 2020).

A2.2 CO_2 emissions and removals resulting from C stock changes in mineral soils

Cropland management modifies SOC storage to varying degrees depending on how specific practices influence C input and output from the soil system. The main management practices that affect soil C stocks in croplands are the type of residue management, type of tillage practices, fertilizer management (both mineral fertilizers and organic amendments), choice of crop and intensity of cropping management (e.g., continuous cropping versus crop rotations with periods of bare fallow), irrigation management, and mixed systems with cropping and pasture or hay in rotating sequences. In addition, drainage and cultivation of organic soils reduces soil C stocks.

Land-use change and management activity can also influence SOC storage by changing erosion rates and subsequent loss of C from a site; some eroded C decomposes in transport and CO_2 is returned to the atmosphere, while the remainder is deposited in another location.

Methodology for estimation of SOC stocks is based on direct measurements from field samplings. However, in this protocol, the estimation of the future variation of SOC stocks shall be made using SOC models (see Annex 1)

A2.3 N2O emissions from all managed soils (extracted and resumed from IPCC 2006, Ch. 11)

Nitrous oxide is produced mainly through two microbial processes: nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic N in the soil.

The emissions of N_2O that result from anthropogenic N inputs or N mineralization occur through both a direct pathway (i.e., directly from the soils to which the N is added/released), and through two indirect pathways: (i) following volatilization of NH_3 and NOx from managed soils and from fossil fuel combustion and biomass burning, and the subsequent redeposition of these gases and their products NH_4^+ and NO_3^- to soils and waters; and (ii) after leaching and runoff of N, mainly as NO_3^-, from managed soils.

A2.3.1 Direct N_2O emissions

In most soils, an increase in available N enhances nitrification and denitrification, which then increases the production of N_2O. Increases in available N can occur through human-induced N additions or change of land-use and/or management practices that mineralize soil organic N. The following N sources are included in the methodology for estimating direct N_2O emissions from managed soils:

- synthetic N fertilizers (FSN);
- organic N applied as fertilizer (e.g., animal manure, crop residues, compost, sewage sludge, rendering waste) (FON);
- urine and dung N deposited on pasture, range and paddock by grazing animals (FPRP);
- N in crop residues (above ground and below ground), including from N-fixing crops (legumes) and from forages during pasture renewal (FCR);
- N mineralization associated with loss of soil organic matter resulting from change of land use or management of mineral soils (FSOM); and

Drainage/management of organic soils (i.e., Histosols) (FOS) is not included in this MRV, as is *a restricted land and practice.*

The total amount of N_2O-N emissions of a given farm or installation (kg N_2O-N yr^{-1}) is calculated as follows:

$$N_2O = N_2Odirect + N_2Oanimal + N_2Oindirect$$

Tier 1

In its most basic form, direct N_2O emissions from managed soils are estimated using the following equation:

$$N_2O_{Direct} - N = N_2O - N_{N\ inputs} + N_2O - N_{PRP}$$

Equation 4.1 (Adapted Eq. 11.1 IPCC 2006, Ch .11)
Direct N_2O emissions from managed soils (Tier 1)

Where:

N_2O_{Direct}–N = annual direct N_2O–N emissions produced from managed soils, kg N_2O–N yr^{-1}
N_2O–$N_{N\ inputs}$ = annual direct N_2O–N emissions from N inputs to managed soils, kg N_2O–N yr^{-1}

$N2O–N_{PRP}$ = annual direct N_2O–N emissions from urine and dung inputs to grazed soils, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1}

F_{ON} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr^{-1}

F_{CR} = annual amount of N in crop residues (above ground and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils, kg N yr^{-1}

F_{SOM} = annual amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N yr^{-1}

F_{PRP} = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr^{-1} (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively)

EF_1 = emission factor for N_2O emissions from N inputs, kg N_2O–N (kg N input)$^{-1}$ (Table A2.1)

EF_{1FR} is the emission factor for N_2O emissions from N inputs to flooded rice, kg N_2O–N (kg N input)$^{-1}$ (Table A2.1)

EF_{3PRP} = emission factor for N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals, kg N_2O–N (kg N input)$^{-1}$; (Table 1) (Note: the subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and Other animals, respectively).

This methodology, therefore, estimates N_2O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilizers, deposited manure, crop residues, sewage sludge), or of mineralization of N in soil organic matter following drainage/ management of organic soils, or cultivation/ land-use change on mineral soils (e.g., Forest Land/Grassland/Settlements converted to Cropland).

Conversion of N_2O–N emissions to N_2O emissions for reporting purposes is performed by using the following equation: $N_2O = N_2O\text{–}N \cdot 44/28$

Tier 2

If more detailed emission factors and corresponding activity data are available to a country than are presented in Equation 4.1, further disaggregation of the terms in the equation can be undertaken. For example, if emission factors and activity data are available for the application of synthetic fertilizers and organic N (F_{SN} and F_{ON}) under different conditions *i*, the following equation shall be used:

$$N_2O_{Direct}\text{–}N = \sum_i \left(F_{SN} + F_{ON}\right)_i \bullet EF_{1i} + \left(F_{CR} + F_{SOM}\right) \bullet EF_1 + N_2O\text{–}N_{OS} + N_2O\text{–}N_{PRP}$$

Equation 4.2 (Adapted Eq. 11.2 IPCC 2006, Ch.11)
Direct N_2O emissions from managed soils (Tier 2)

where:

EF_{1i} = emission factors developed for N_2O emissions from synthetic fertilizers and organic N application under conditions *i* (kg N_2O–N (kg N input)$^{-1}$); *i* = 1, ...n.

Equation 4.2 may be modified in a variety of ways to accommodate any combination of N source-, crop type-, management-, land use-, climate-, soil- or other condition-specific emission factors that a country, region or farm may be able to obtain for each of the individual N input variables (F_{SN}, F_{ON}, F_{CR}, F_{SOM}, F_{PRP}).

Conversion of N_2O–N emissions to N_2O emissions for reporting purposes is performed by using the following equation: $N_2O = N_2O\text{–}N \cdot 44/28$

Tier 3

Tier 3 methods are modelling or measurement approaches. Models are useful because in appropriate forms they can relate the soil and environmental variables responsible for N_2O emissions to the size of those emissions. These relationships may then be used to predict emissions from whole countries or regions for which experimental measurements are impracticable. Models should only be used after validation by representative experimental measurements. Care should also be taken to ensure that the emission estimates developed using models or measurements account for all anthropogenic N_2O emissions.

Choice of emission factors Tiers 1 and 2

Two emission factors (EF) are needed to estimate direct N_2O emissions from managed soils. The default values presented here may be used in the Tier 1 equation or in the Tier 2 equation in combination with country-specific EFs. The first EF (EF_1) refers to the amount of N_2O emitted from the various synthetic and organic N applications to soils, including crop residue and mineralization of soil organic carbon in mineral soils due to land-use change or management. The second EF (EF_3) estimates the amount of N_2O emitted from urine and dung N deposited by grazing animals on pasture, range and paddock. Default emission factors for the Tier 1 method are summarized in Table A2.1.

Table A2.1 | Default emission factors to estimate direct N_2O emissions from managed soils (From Table 11.1 IPCC, 2006; Ch 11)

Emission factor	Default value	Uncertainty range
EF_1 for N additions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil as a result of loss of soil carbon [kg N_2O–N (kg N)$^{-1}$]	0.01	0.003 - 0.03
EF_{1FR} for flooded rice fields [kg N_2O–N (kg N)$^{-1}$]	0.003	0.000 - 0.006
$EF_{3PRP, CPP}$ for cattle (dairy, non-dairy and buffalo), poultry and pigs [kg N_2O–N (kg N)$^{-1}$]	0.02	0.007 - 0.06
$EF_{3PRP, SO}$ for sheep and 'other animals' [kg N_2O–N (kg N)$^{-1}$]	0.01	0.007 - 0.06

In many cases, the EF_1 could be disaggregated based on (1) environmental factors (climate, soil organic C content, soil texture, drainage and soil pH); and (2) management-related factors (N application rate per fertilizer type, type of crop, with differences between legumes, non-leguminous arable crops, and grass). Committed farmers that can disaggregate their activity data from all or some of these factors may choose to use disaggregated emission factors with the Tier 2 approach.

The default value for EF_{3PRP} is 2% of the N deposited by all animal types except 'sheep' and 'other' animals. For these latter species, a default emission factor of 1% of the N deposited may be used.

Choice of activity data

Tiers 1 and 2:

This section describes generic methods for estimating the amount of various N inputs to soils (F_{SN}, F_{ON}, F_{PRP}, F_{CR}, F_{SOM}) that are needed for the Tier 1 and Tier 2 methodologies (Equations 4.1 and 4.2).

Applied synthetic fertilizer (F_{SN})

The term F_{SN} refers to the annual amount of synthetic N fertilizer applied to soils. It is estimated from the total amount of synthetic fertilizer consumed annually. If enough data are available, fertilizer use may be disaggregated by fertilizer type, crop type and climatic regime for major crops.

Applied organic N fertilizers (F_{ON})

The term "applied organic N fertilizer" (F_{ON}) refers to the amount of organic N inputs applied to soils other than by grazing animals and is calculated using Equation 2.3. This includes applied animal manure, sewage sludge applied to soil, compost applied to soils, as well as other organic amendments of regional importance to agriculture (e.g., rendering waste, guano, brewery waste, etc.).

Organic N fertilizer (F_{ON}) is calculated using Equation 4.3:

$$F_{ON} = F_{AM} + F_{SEW} + F_{COMP} + F_{OOA}$$

Equation 4.3 (Adapted Eq. 11.3 IPCC 2006, Ch. 11)
Direct N_2O emissions from managed soils (Tier 2)

where:

F_{ON} = total annual amount of organic N fertilizer applied to soils other than by grazing animals, kg N yr^{-1}

F_{AM} = annual amount of animal manure N applied to soils, kg N yr^{-1}

F_{SEW} = annual amount of total sewage N (coordinate with Waste Sector to ensure that sewage N is not double-counted) that is applied to soils, kg N yr^{-1}

F_{COMP} = annual amount of total compost N applied to soils (ensure that manure N in compost is not double-counted), kg N yr^{-1}

F_{OOA} = annual amount of other organic amendments used as fertilizer (e.g., rendering waste, guano, brewery waste, etc.), kg N yr^{-1}

The term F_{AM} is determined by adjusting the amount of manure N available (N_{MMS_Avb}) for the amount of managed manure used for feed ($Frac_{FEED}$), burned for fuel ($Frac_{FUEL}$), or used for construction ($Frac_{CNST}$) as shown in Equation 4.4. Data for $Frac_{FUEL}$, $Frac_{FEED}$, $Frac_{CNST}$ can be obtained from official statistics or a survey of experts. However, if these data are not available use N_{MMS_Avb} as F_{AM} without adjusting for $Frac_{FUEL}$, $Frac_{FEED}$, $Frac_{CNST}$.

$$F_{AM} = N_{MMSAvb} \cdot [1 - (Frac_{FEED} + Frac_{FUEL} + Frac_{CNST})]$$

Equation 4.4 (Adapted Eq. 11.4 IPCC 2006, Ch. 11)
N from animal manure applied to soils (Tier 1)

where:

F_{AM} = annual amount of animal manure N applied to soils, kg N yr^{-1}

N_{MMS_Avb} = amount of managed manure N available for soil application, feed, fuel or construction, kg N yr^{-1} (IPCC 2006, Ch. 10)

$Frac_{FEED}$ = fraction of managed manure used for feed

$Frac_{FUEL}$ = fraction of managed manure used for fuel

$Frac_{CNST}$ = fraction of managed manure used for construction

Urine and dung from grazing animals (F_{PRP})

The term F_{PRP} refers to the annual amount of N deposited on pasture, range and paddock soils by grazing animals. It is important to note that the N from managed animal manure applied to soils is included in the F_{AM} term of F_{ON}. The term F_{PRP} is estimated using Equation 4.5 from the number of animals in each livestock species/category T (N(T)), the annual average amount of N excreted by each livestock species/category T ($Nex_{(T)}$), and the fraction of this N deposited on pasture, range and paddock soils by each livestock species/category T ($MS_{(T,PRP)}$). The data needed for this equation can be obtained from IPCC 2006, Ch. 10).

Equation 4.5 provides an estimate of the amount of N deposited by grazing animals:

$$F_{PRP} = \Sigma_T [(N_{(T)} \bullet Nex_{(T)}) \bullet MS_{(T,PRP)}]$$

Equation 4.5 (Adapted Eq. 11.5 IPCC 2006, Ch. 11)
N in urine and dung deposited by grazing animals on pasture, range and paddok (Tier 1)

where:

F_{PRP} = annual amount of urine and dung N deposited on pasture, range, paddock and by grazing animals, kg N yr^{-1}.

$N_{(T)}$ = number of head of livestock species/category T in the country (see Chapter 10, Section 10.2) Nex(T) = annual average N excretion per head of species/category T in the farm, kg N $animal^{-1}$ yr^{-1} (see IPCC 2006, Ch. 10)

$MS_{(T,PRP)}$ = fraction of total annual N excretion for each livestock species/category T that is deposited on pasture, range and paddock (see IPCC 2006, Ch. 10).

Crop residue N, including N-fixing crops and forage/pasture renewal, returned to soils, (F_{CR}):

The term F_{CR} refers to the amount of N in crop residues (above ground and below ground), including N-fixing crops, returned to soils annually. It also includes the N from N-fixing and non-N-fixing forages mineralized during forage or pasture renewal. The method accounts for the effect of residue burning or other removal of residues (direct emissions of N_2O from residue burning are addressed under IPCC 2006, Ch. 2). Because different crop types vary in residue: yield ratios, renewal time and N contents, separate calculations should be performed for major crop types and then N values from all crop types are summed up. At a minimum, it is recommended that crops be segregated into: 1) non-N-fixing grain crops (e.g., maize, rice, wheat, barley); 2) N-fixing grains and pulses (e.g., soybean, dry beans, chickpea, lentils); 3) root and tuber crops (e.g., potato, sweet potato, cassava); 4) N-fixing forage crops (alfalfa, clover); and 5) other forages including perennial grasses and grass/clover pastures. Equation 4.6 provides the equation to estimate N from crop residues and forage/pasture renewal, for a Tier 1 approach.

$$F_{CR} = \sum_{T} \left\{ \begin{array}{l} Crop_{(T)} \bullet Frac_{Renew(T)} \bullet \\ \left[\left(Area_{(T)} - Area\,burnt_{(T)} \bullet C_f \right) \bullet R_{AG(T)} \bullet N_{AG(T)} \bullet \right. \\ \left. \left(1 - Frac_{Remove(T)}\right) + Area_{(T)} \bullet R_{BG(T)} \bullet N_{BG(T)} \right] \end{array} \right\}$$

Equation 4.6 (Adapted Eq. 11.6 IPCC 2006, Ch. 11)
N from crop residues and forage/pasture renewal (Tier 1)

where:

F_{CR} = annual amount of N in crop residues (above and below ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually, kg N yr^{-1}

$Crop_{(T)}$ = harvested annual dry matter yield for crop T, kg DM ha^{-1}

$Area_{(T)}$ = total annual area harvested of crop T, ha yr^{-1}

Area burnt $_{(T)}$ = annual area of crop T burnt, ha yr^{-1}

C_f = combustion factor (dimensionless) (refer to IPCC 2006 Ch. 2)

Frac $_{Renew\ (T)}$ = fraction of total area under crop T that is renewed annually. For farms where pastures are renewed on average every X years, $Frac_{Renew}$ = 1/X. For annual crops $Frac_{Renew}$ = 1 R $_{AG(T)}$ = ratio of aboveground residues dry matter (AG $_{DM(T)}$) to harvested yield for crop T ($Crop_{(T)}$), kg d.m. (kg DM.)$^{-1}$,

= AG $_{DM(T)}$ • 1000 / $Crop_{(T)}$

N $_{AG(T)}$ = N content of aboveground residues for crop T, kg N (kg d.m.) $^{-1}$, (Table 11.2, IPCC 2006, Ch.11)

Frac $_{Remove(T)}$ = fraction of aboveground residues of crop T removed annually for purposes such as feed, bedding and construction, kg N (kg crop-N)$^{-1}$. Survey of experts in country is required to obtain data. If data for $Frac_{Remove}$ are not available, assume no removal. RBG(T) = ratio of belowground residues to harvested yield for crop T, kg d.m. (kg DM)$^{-1}$. If alternative data are not available, R $_{BG(T)}$ may be calculated by multiplying R $_{BG\text{-}BIO}$ in Table 11.2 (IPCC 2006, Ch. 11) by the ratio of total aboveground biomass to crop yield (= [(AG $_{DM(T)}$ • 1000 + Crop / Crop],(also calculating AG from the information in Table 11.2).

N $_{BG(T)}$ = N content of belowground residues for crop T, kg N (kg DM)$^{-1}$, (Table 11.2, IPCC 2006 Ch.11)

T = crop or forage type

Since yield statistics for many crops are reported as field-dry or fresh weight, a correction factor can be applied to estimate dry matter yields ($Crop_{(T))}$ where appropriate (Equation 4.7). The proper correction to be used is dependent on the standards used in yield reporting, which may vary between countries. Alternatively, the default values for dry matter content given in Table 11.2 (IPCC 2006, Ch.11) may be used.

$$Crop_{(T)} = Yield\,Fresh_{(T)} \cdot DRY$$

Equation 4.7 (Adapted Eq. 11.7 IPCC 2006, Ch. 11)
Dry-weight correction of reported crop yields

where:

Crop $_{(T)}$ = harvested dry matter yield for crop $_{T}$, kg DM ha^{-1}

Yield_Fresh $_{(T)}$ = harvested fresh yield for crop $_{T}$, kg fresh weight ha^{-1}

DRY = dry matter fraction of harvested crop $_{T}$, kg DM (kg fresh weight)$^{-1}$

Mineralized N resulting from loss of soil organic C stocks in mineral soils through land-use change or management practices (F_{SOM}):

The term F_{SOM} refers to the amount of N mineralized from loss in soil organic C in mineral soils through land use change or management practices. Land-use change and a variety of management practices can have a significant impact on soil organic C storage. Organic C and N are intimately linked in soil organic matter. Where soil C is lost through oxidation as a result of land-use or management change, this loss will be accompanied by a simultaneous mineralization of N. Where a loss of soil C occurs, this mineralized N is regarded as an additional source of N available for conversion to N_2O; just as mineral N released from decomposition of crop residues, for example, becomes a source. The same default emission factor (EF_1) is applied to mineralized N from soil organic matter loss as is used for direct emissions resulting from fertilizer and organic N inputs to agricultural land.

For all situations where soil C losses occur, the Tier 2 method for calculating the release of N by mineralization is shown below.

Calculation steps for estimating changes in N supply from mineralization

Step 1:

Calculate the average annual loss of soil C ($\Delta C_{Mineral, LU}$) for the area, over the inventory period, using Equation 1. Using the Tier 1 approach, the value for ΔC Mineral, LU will have a single value for all land-uses and management systems. Using Tier 2, the value for $\Delta C_{Mineral, LU}$ will be disaggregated by individual land-use and/or management systems.

Step 2:

Estimate the N mineralized because of this loss of soil C (FSOM), using Equation 4.8:

$$F_{SOM} = \sum_{LU}\left[\left(\Delta C_{Mineral,\ LU} \bullet \frac{1}{R}\right) \bullet 1000\right]$$

Equation 4.8 (Adapted Eq. 11.8 IPCC 2006, Ch. 11)
N mineralised in mineral soils as a result of loss of soil c through change in land use or management (tiers 2)

where:

F_{SOM} = the net annual amount of N mineralized in mineral soils as a result of loss of soil carbon through change in land use or management, kg N

$C_{Mineral, LU}$ = average annual loss of soil carbon for each land-use type (LU), tonnes C Using Tier 2 the value for $\Delta C_{mineral}$, LU will be disaggregated by individual land-use and/or management systems.

R = C:N ratio of the soil organic matter. A default value of 15 (uncertainty range from 10 to 30) for the C:N ratio (R) may be used for situations involving land-use change from Forest Land or Grassland to Cropland, in the absence of more specific data for the area. A default value of 10 (range from 8 to 15) may be used for situations involving management changes on Cropland Remaining Cropland. C:N ratio can change over time, land use, or management practice.

LU = land-use and/or management system type

Step 3:

For Tier 2, FSOM is calculated by summing across all land-uses and/or management system types (LU). It is also good practice to use specific data for the C:N ratios for the disaggregated land areas, if these are available, in conjunction with the data for carbon changes.

A2.3.2 Indirect N_2O emissions

In addition to the direct emissions of N_2O from managed soils that occur through a direct pathway (i.e., directly from the soils to which N is applied), emissions of N_2O also take place through two indirect pathways. The first of these pathways is the volatilization of N as NH_3 and oxides of N (NO_x), and the deposition of these gases and their products NH_4^+ and NO_3^- onto soils and the surface of lakes and other waters. The sources of N as NH_3 and NO_x are not confined to agricultural fertilizers and manures, but also include fossil fuel combustion and biomass burning. Thus, these processes cause N_2O emissions in an exactly analogous way to those resulting from deposition of agriculturally derived NH_3 and NO_x, following the application of synthetic and organic N fertilizers and /or urine and dung deposition from grazing animals.

The second pathway is the leaching and runoff from land of N from synthetic and organic fertilizer additions, crop residues, mineralization of N associated with loss of SOC through land-use/cover change or management practices, and urine and dung deposition from grazing animals. Some of the inorganic N in or on the soil, mainly in the NO_3^- form, may bypass biological retention mechanisms in the soil/vegetation system by transport in overland water flow (runoff) and/or flow through soil macropores or pipe drains. Where NO_3^- is present in the soil in excess of biological demand, e.g., under cattle urine patches, the excess leaches through the soil profile. The nitrification and denitrification processes described at the beginning of this chapter transform some of the NH_4^+ and NO_3^- to N_2O. This may take place in the groundwater below the land to which the N was applied, or in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers and

estuaries (and their sediments) into which the land drainage water eventually flows.

This methodology described in this Chapter addresses the following N sources of indirect N_2O emissions from managed soils arising from agricultural inputs of N:

- synthetic N fertilizers (F_{SN}); (urea, Calcium Ammonium Nitrate, ammonium sulphate, ammonium nitrate, etc.);
- organic N applied as fertilizer (e.g., applied animal manure/slurry, compost, sewage sludge, rendering waste and other organic amendments) (F_{ON});
- urine and dung N deposited on pasture, range and paddock by grazing animals (F_{PRP});
- N in crop residues (above- and belowground), including N-fixing crops and forage/pasture renewal returned to soils (F_{CR}); and
- N mineralization associated with loss of soil organic matter resulting from change of land use or management on mineral soils (F_{SOM}).

Choice of methods

Tier 1

Volatilization, $N_2O_{(ATD)}$:

The N_2O emissions from atmospheric deposition of N volatilized from managed soil are estimated using Equation 4.9:

$$N_2O_{(ATD)}\text{–}N = [(F_{SN} \bullet Frac_{GASF}) + ((F_{ON} + F_{PRP}) \bullet Frac_{GASM})] \bullet EF_4$$

Equation 4.9 (Adapted Eq. 11.9 IPCC 2006, Ch. 11)
N_2O from atmospheric deposition of N volatilised from managed soils (Tier 1)

where:

$N_2O_{(ATD)}$ – N = annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1}

$Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x, kg N volatilized (kg of N applied)$^{-1}$

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr^{-1}

F_{PRP} = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr^{-1}

$Frac_{GASM}$ = fraction of applied organic N fertilizer materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_3 and NO_x, kg N volatilized (kg of N applied or deposited)$^{-1}$

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilized)$^{-1}$]

Conversion of $N_2O_{(ATD)}$ -N emissions to N_2O emissions for reporting purposes is performed by using the following equation: $N_2O_{(ATD)} = N_2O_{(ATD)}$–N • 44/28

$$N_2O_{(L)}\text{–}N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) \bullet Frac_{LEACH-(H)} \bullet EF_5$$

Equation 4.10 (Adapted Eq. 11.10 IPCC 2006, Ch. 11)
N_2O from N leaching/runoff from managed soils in regions where leaching/runoff occurs (Tier 1)

Leaching/Runoff, $N_2O_{(L)}$:

The N_2O emissions from leaching and runoff in regions where leaching and runoff occurs are estimated using Equation 4.10:

where:

$N_2O_{(L)}$ – N = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs, kg N yr^{-1}

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N yr^{-1}

F_{PRP} = annual amount of urine and dung N deposited by grazing animals in regions where leaching/runoff occurs, kg N yr^{-1} (from Equation 2.5)

F_{CR} = amount of N in crop residues (above- and belowground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs, kg N yr^{-1}

F_{SOM} = annual amount of N mineralized in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, kg N yr^{-1} (from Equation 2.8).

$Frac_{LEACH-(H)}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$

Conversion of $N_2O_{(L)}$ –N emissions to N_2O emissions for reporting purposes is performed by using the following equation: $N_2O_{(L)} = N_2O_{(L)}$ –N . 44/28.

Tier 2

If more detailed emission, volatilization or leaching factors are available, further disaggregation of the terms in the equations can also be undertaken. For example, if specific volatilization factors are available for the application of synthetic fertilizers (F_{SN}) under different conditions i, Equation 4.11 would be expanded to become:

$$N_2O_{(ATD)}\text{–}N = \left\{\sum_i \left(F_{SN_i} \bullet Frac_{GASF_i}\right) + \left[\left(F_{ON} + F_{PRP}\right) \bullet Frac_{GASM}\right]\right\} \bullet EF_4$$

Equation 4.11 (Adapted Eq. 11.11 IPCC 2006, Ch. 11)
N_2O from atmospheric deposition of N volatilised from managed soils (Tier 2)

where:

$N_2O_{(ATD)}$ –N = annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O–N yr^{-1}

F_{SNi} = annual amount of synthetic fertilizer N applied to soils under different conditions i, kg N yr_{-1}

$Frac_{GASFi}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x under different conditions i, kg N volatilized (kg of N applied)$^{-1}$

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr^{-1}

F_{PRP} = annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr^{-1}

$Frac_{GASM}$ = fraction of applied organic N fertilizer materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_3 and NO_x, kg N volatilized (kg of N applied or deposited)$^{-1}$

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH_3–N + NO_x–N volatilized)$^{-1}$]

Conversion of $N_2O_{(ATD)}$ –N emissions to $N_2O_{(ATD)}$ emissions for reporting purposes is performed by using the following equation:

$$N_2O_{(ATD)} = N_2O_{(ATD)}\text{–}N \bullet 44/28$$

Tier 3

Tier 3 methods are modelling or measurement approaches. Models are useful as they can relate the variables responsible for the emissions to the size of those emissions. These relationships may then be used to predict emissions from whole countries or regions for which experimental measurements are impracticable.

Choice of emission, volatilization and leaching factors

The method for estimating indirect N_2O emissions includes two emission factors: one associated with volatilized and re-deposited N (EF_4), and the second associated with N lost through leaching/runoff (EF_5). The method also requires values for the fractions of N that are lost through volatilization ($Frac_{GASF}$ and $Frac_{GASM}$) or leaching/runoff ($Frac_{LEACH-(H)}$). The default values of all these factors are presented in Table 2. Note that in the Tier 1 method, for humid regions or in dryland regions where irrigation

(other than drip irrigation) is used, the default Frac $_{LEACH-(H)}$ is 0.30. For dryland regions, where precipitation is lower than evapotranspiration throughout most of the year and leaching is unlikely to occur. The default values of all these factors are presented in Table A2.2.

Table A2.2 | Default emission, volatilization and leaching factors for indirect N_2O emissions from managed soils (From Table 11.1 IPCC, 2006; Ch 11).

Emission factor	Default value	Uncertainty range
EF_4 [N volatilisation and re-deposition], kg N_2O–N (kg NH_3–N + NO_X–N volatilised)$^{-1}$	0.010	0.002 - 0.05
EF_5 [leaching/runoff], kg N_2O–N (kg N leaching/ runoff)$^{-1}$	0.0075	0.0005 - 0.025
$Frac_{GASF}$ [Volatilisation from synthetic fertiliser], (kg NH_3–N + NO_x–N) (kg N applied)$^{-1}$	0.10	0.03 - 0.3
$Frac_{GASM}$ [Volatilisation from all organic N fertilisers applied, and dung and urine deposited by grazing animals], (kg NH_3–N+NO_x–N) (kg N applied or deposited)$^{-1}$	0.20	0.05 - 0.5
$Frac_{LEACH-(H)}$ [N losses by leaching/runoff for regions where Σ (rain in rainy season) -Σ (PE in same period) > soil water holding capacity, OR where irrigation (except drip irrigation) is employed], kg N (kg N additions or deposition by grazing animals)$^{-1}$	0.30	0.1 - 0.8

Choice of activity data:

In order to estimate indirect N_2O emissions from the various N additions to managed soils, the parameters F_{SN}, F_{ON}, F_{PRP}, F_{CR}, F_{SOM} need to be estimated.

Applied synthetic fertilizer (F_{SN}) :

The term FSN refers to the annual amount of synthetic fertilizer N applied to soils. Refer to the activity data section on direct N_2O emissions from managed soils and obtain the value for F_{SN}.

Applied organic N fertilizers (F_{ON}):

The term F_{ON} refers to the amount of organic N fertilizer materials intentionally applied to soils. Refer to the activity data section on direct N_2O emissions from managed soils and obtain the value for F_{ON}.

Urine and dung from grazing animals (F_{PRP}):

The term F_{PRP} refers to the amount of N deposited on soil by animals grazing on pasture, range and paddock. Refer to the activity data section on direct N_2O emissions from managed soils and obtain the value for F_{PRP}.

Crop residue N, including N from N-fixing crops and forage/pasture renewal, returned to soils (F_{CR}):

The term F_{CR} refers to the amount of N in crop residues (above- and belowground), including N-fixing crops, returned to soils annually. It also includes the N from N-fixing and non-N-fixing forages mineralized during forage/ pasture renewal. Refer to the activity data section on direct N_2O emissions from managed soils and obtain the value for F_{CR}.

Mineralized N resulting from loss of soil organic C stocks in mineral soils (F_{SOM}):

The term F_{SOM} refers to the amount of N mineralized from the loss of soil organic C in mineral soils through land-use change or management practices. Refer to the activity data section on direct N_2O emissions from managed soils and obtain the value for F_{SOM}.

A2.3.3. CO_2 emissions from liming

Liming is used to reduce soil acidity and improve plant growth in managed systems, particularly agricultural lands and managed forests. Adding carbonates to soils in the form of lime such as calcitic limestone ($CaCO_3$), or dolomite ($CaMg(CO_3)_2$ leads to CO_2 emissions as the carbonate limes dissolve and release bicarbonate ($2HCO_3^-$), which evolves into CO_2 and water (H_2O).

Choice of method

Tier 1

CO_2 Emissions from additions of carbonate limes to soils can be estimated with Equation 4.12:

$$CO_2\text{–}C\ Emission = (M_{Limestone} \bullet EF_{Limestone}) + (M_{Dolomite} \bullet EF_{Dolomite})$$

Equation 4.12 (Adapted Eq. 11.12 IPCC 2006, Ch. 11)
Annual CO_2 emissions from lime application

where:

CO_2–C Emission = annual C emissions from lime application, tonnes C yr^{-1}

M = annual amount of calcic limestone ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$), tonnes yr^{-1}

EF = emission factor, tonne of C (tonne of limestone or dolomite) $^{-1}$

Procedural steps for calculations:

The steps for estimating CO_2-C emissions from liming are:

Step 1:

Estimate the total amount (M) of carbonate containing lime applied annually to soils in the country, differentiating between limestone and dolomite.

Step 2:

Apply an overall emission factor (EF) of 0.12 for limestone and 0.13 for dolomite. These are equivalent to carbonate carbon contents of the materials (12% for CaCO3, 13% for $CaMg(CO_3)_2$).

Step 3:

Multiply the total amounts of limestone and dolomite by their respective emission factors and sum the two values to obtain the total CO_2–C emission.

Multiply by 44/12 to convert CO_2–C emissions into CO_2.

Tier 2

Tier 2 inventories also use Equation 4.12 and procedural steps, which were provided in the Tier 1 approach, but incorporate country-specific data to derive emission factors (EF). Overall, the CO_2 emissions from liming are expected to be less than using the Tier 1 approach, which assumes that all C in applied lime is emitted as CO_2 in the year of application. However, emissions are likely to be less than assumed using the Tier 1 approach because the amount of CO_2 emitted after liming will depend on site specific influences and transport of dissolved inorganic C through rivers and lakes to the ocean. Tier 2 emission factors could be used to better approximate the emissions.

Choice of emission factors:

Tier 1

Default emission factors (EF) are 0.12 for limestone and 0.13 for dolomite.

Tier 2

Derivation of emission factors using country-specific data could entail differentiation of sources with variable compositions of lime; different carbonate liming materials (limestone as well as other sources such as marl and shell deposits) can vary somewhat in their C content and overall purity. Each material would have a unique emission factor based on the C content. Country-specific emission factors could also account for the proportion of carbonate-C from liming that is emitted to the atmosphere as CO_2. Country-specific emission factors can be derived

if there are enough data and understanding of inorganic carbon transformations, in addition to knowledge about transport of aqueous Ca, Mg, and inorganic C. It is good practice to document the source of information and method used for deriving country-specific values in the reporting process.

A2.3.4 CO_2 emissions from urea fertilization

Adding urea to soils during fertilization leads to a loss of CO_2 that was fixed in the industrial production process. Urea ($CO(NH_2)_2$) is converted into ammonium (NH_4^+), hydroxyl ion (OH^-), and bicarbonate (HCO_3^-), in the presence of water and urease enzymes.

Choice of method

Tier 1

CO_2 emissions from urea fertilization can be estimated with Equation 4.13:

$$CO_2\text{–}C\ Emission = M \bullet EF$$

Equation 4.13 (Adapted Eq. 11.13 IPCC 2006, Ch. 11)
Annual CO_2 emissions from urea application

where:

CO_2–C Emission = annual C emissions from urea application, tonnes C yr^{-1}

M = annual amount of urea fertilization, tonnes urea yr^{-1}

EF = emission factor, tonne of C (tonne of urea)[1]

Procedural Steps for Calculations:

The steps for estimating CO_2–C emissions from urea applications are:

Step 1:

Estimate the total amount of urea applied annually to a soil in the farm (M).

Step 2:

Apply an overall emission factor (EF) of 0.20 for urea, which is equivalent to the carbon content of urea on an atomic weight basis (20% for $CO(NH_2)_2$). A default -50% uncertainty may be applied

Step 3:

Estimate the total CO_2–C emission based on the product of the amount of urea applied and the emission factor.

Multiply by 44/12 to convert CO_2–C emissions into CO_2. Urea is often applied in combination with other nitrogenous fertilizers, particularly in solutions, and it will be necessary to estimate the proportion of urea in the fertilizer solution for M. If the proportion is not known, it is considered good practice to assume that the entire solution is urea, rather than potentially under-estimating emissions for this subcategory.

Tier 2

Tier 2 inventories also use Equation 4.13 and procedural steps, which were provided in the Tier 1 approach, but incorporate country-specific information to estimate emission factors.

Choice of emission factor

Tier 1

The default emission factor (EF) is 0.20 for carbon emissions from urea applications.

Tier 2

Like carbonate limes, all C in urea may not be emitted in the year of application. If enough data and understanding of inorganic C transformation are available, country-specific specific emission factors could be derived.

A2.3.5 Emissions from livestock

Livestock production can result in methane (CH_4) emissions from enteric fermentation and both CH_4 and nitrous oxide (N_2O) emissions from livestock manure management systems. Cattle are an important source of CH_4 in many countries because of their large population and high CH_4 emission rate due to their ruminant digestive system. Methane emissions from manure management tend to be smaller than enteric emissions, with the most substantial emissions associated with confined animal management operations where manure is handled in liquid-based systems. Nitrous oxide

emissions from manure management vary significantly between the types of management system used and can also result in indirect emissions due to other forms of nitrogen loss from the system.

The methods for estimating CH_4 emissions from livestock require definitions of livestock subcategories, annual populations and, for higher Tier methods, feed intake and characterization:

- CH_4 emissions from enteric fermentation;
- CH_4 emissions from manure management (manure collection, treatment, and storage) in livestock farms;
- N_2O emissions during manure management in livestock farms and from Managed Soils (direct and indirect) when manure is used as soil amendment, which was previously described.

Livestock population and feed characterization

Steps to define categories and subcategories of livestock

The steps are:

- Identify livestock species applicable to each emission source category: The livestock species that contribute to more than one emission source category should first be listed. These species are typically: cattle, buffalo, sheep, goats, swine, horses, camels, mules/asses, and poultry.
- Review the emission estimation method for each relevant source category: For the source categories of Enteric Fermentation, identify the emission estimating method for each species for that source category.
- Identify the most detailed characterization required for each livestock species: Based on the assessments for each species under each source category, identify the most detailed characterization required to support each emissions estimate for each species.

Choice of method

Tier 1: basic characterization for livestock populations:

Basic characterization for Tier 1 is likely to be enough for most animal species in most farms. For this approach it is good practice to collect the following livestock characterization data to support the emissions estimates:

Livestock species and categories:

A complete list of all livestock populations that have default emission factor values must be developed (e.g., dairy cows, other cattle, buffalo, sheep, goats, camels, llamas, alpacas, deer, horses, rabbits, mules and asses, swine, and poultry) if these categories are relevant to the farm. More detailed categories should be used if the data are available.

Tier 2: enhanced characterization for livestock populations

The Tier 2 livestock characterization requires detailed information on:

- Definitions for livestock subcategories;
- Livestock population by subcategory, with consideration for estimation of annual population as per Tier 1; and
- Feed intake estimates for the typical animal in each subcategory.

The livestock population subcategories are defined to create relatively homogenous sub-groupings of animals. By dividing the population into these subcategories, country-specific variations in age structure and animal performance within the overall livestock population can be reflected. The Tier 2 characterization methodology seeks to define animals, animal productivity, diet quality and management circumstances to support a more accurate estimate of feed intake for use in estimating methane production from enteric fermentation.

Definitions for livestock subcategories

It is good practice to classify livestock populations into subcategories for each species according to age, type of production, and sex.

Representative livestock categories for doing this are shown in Table 3. Further subcategories are also possible:

- Cattle and buffalo populations should be classified into at least three main subcategories: mature dairy, other mature, and growing cattle. Depending on the level of detail in the emissions estimation method, subcategories can be further classified based on animal or feed characteristics. For example, growing / fattening cattle could be further subdivided into those cattle that are fed a high-grain diet and housed in dry lots vs. those cattle that are grown and finished solely on pasture.
- Subdivisions like those used for cattle and buffalo can be used to further segregate the sheep population in order to create subcategories with relatively homogenous characteristics. For example, growing lambs could be further segregated into lambs finished on pasture vs. lambs finished in a feedlot. The same approach applies to national goat herds.
- Subcategories of swine could be further segregated based on production conditions. For example, growing swine could be further subdivided into growing swine housed in intensive production facilities vs. swine that are grown under free-range conditions.

Table A2.3 | Representative livestock categories (Adapted from Table 10.1, IPCC 2006, Ch 10).

Main categories	Subcategories
Mature Dairy Cow or Mature Dairy Buffalo	• High-producing cows that have calved at least once and are used principally for milk production • Low-producing cows that have calved at least once and are used principally for milk production
Other Mature Cattle or Mature Non-dairy Buffalo	Females: • Cows used to produce offspring for meat • Cows used for more than one production purpose: milk, meat, draft Males: • Bulls used principally for breeding purposes • Bullocks used principally for draft power
Growing Cattle or Growing Buffalo	• Calves pre-weaning • Replacement dairy heifers • Growing / fattening cattle or buffalo post-weaning • Feedlot-fed cattle on diets containing > 90 % concentrates
Mature Ewes	• Breeding ewes for production of offspring and wool production • Milking ewes where commercial milk production is the primary purpose
Other Mature Sheep (>1 year)	• No further sub-categorisation recommended
Growing Lambs	• Intact males • Castrates • Females

For each of the representative animal categories defined, the following information is required:

- annual average population (number of livestock);
- average daily feed intake (megajoules (MJ) per day and / or kg per day of dry matter); and
- methane conversion factor (percentage of feed energy converted to methane).

Generally, data on average daily feed intake are not available, particularly for grazing livestock. Consequently, the following general data should be collected for estimating the feed intake for each representative animal category:

- weight (kg);
- average weight gain per day (kg);
- feeding situation: confined, grazing, pasture conditions;
- milk production per day (kg/day) and fat content (%);
- average amount of work performed per day (hours day^{-1});
- percentage of females that give birth in a year;
- wool growth;
- number of offspring; and
- feed digestibility (%).

Feed intake estimates

Tier 2 emissions estimates require feed intakes for a representative animal in each subcategory. Feed intake is typically measured in terms of gross energy (e.g., megajoules (MJ) per day) or dry matter (e.g., kilograms (kg) per day). Dry matter is the amount of feed consumed (kg) after it has been corrected for the water content in the complete diet. For example, consumption of 10 kg of a diet that contains 70% dry matter would result in a dry matter intake of 7 kg. The remainder of this subsection presents the typical data requirements and equations used to estimate feed intake for cattle, buffalo, and sheep. Feed intake for other species can be estimated using similar country-specific methods appropriate for each. For all estimates of feed intake, good practice is to:

- Collect data to describe the animal's typical diet and performance in each subcategory;
- Estimate feed intake from the animal performance and diet data for each subcategory. In some cases, the equations may be applied on a seasonal basis, for example under conditions in which livestock gain weight in one season and lose weight in another.
- The following animal performance data are required for each animal subcategory to estimate feed intake for the subcategory:
- Weight (W), kg: Live-weight data should be collected for each animal subcategory. Comparing live-weight data with slaughter weight data is a useful cross-check to assess whether the live-weight data are representative of farm conditions. However, slaughter-weight data should not be used in place of live-weight data as it fails to account for the complete weight of the animal. Additionally, it should be noted that the relationship between live-weight and slaughter-weight varies with breed and body condition.

For cattle, buffalo and mature sheep, the yearly average weight for each animal category (e.g., mature beef cows) is needed. For young sheep, weights are needed at birth, weaning, one year of age or at slaughter if slaughter occurs within the year.

- Average weight gain per day (WG), kg day^{-1}: Data on average weight gain are generally collected for feedlot animals and young growing animals. Mature animals are generally assumed to have no net weight gain or loss over an entire year. Mature animals frequently lose weight during the dry season or during temperature extremes and gain weight during the following season. However, increased emissions associated with this weight change are likely to be small. Reduced intakes and emissions associated with weight loss are largely balanced by increased intakes and emissions during the periods of gain in body weight.

- Mature weight (MW), kg: The mature weight of the adult animal of the inventoried group is required to define a growth pattern, including the feed and energy required for growth. For example, the mature weight of a breed or category of cattle or buffalo is generally considered to be the body weight at which skeletal development is complete. Estimates of mature weight are typically available from livestock specialists and producers.

- Average number of hours worked per day: For draft animals, the average number of hours worked per day must be determined.

- Feeding situation: The feeding situation that most accurately represents the animal subcategory must be determined using the definitions shown in Table 4. If the feeding situation lies between the definitions, the feeding situation should be described in detail. This detailed information may be needed when calculating the enteric fermentation emissions, because interpolation between the feeding situations may be necessary to assign the most appropriate coefficient.

For cattle and other ruminants that graze pastures, this forage has digestibility ranging 55-75%. If they graze pastures with low quality forage, digestibility ranges 45-55%.

Average daily milk production (kg day^{-1}):

These data are for milking ewes, dairy cows and buffalo. The average daily production should be calculated by dividing the total annual production by 365 or reported as average daily production along with days of lactation per year, or estimated using seasonal production divided by number of days per season. If using seasonal production data, the emission factor must be developed for that seasonal period.

- Fat content (%): Average fat content of milk is required for lactating cows, buffalo, and sheep producing milk for human consumption.

- Percent of females that give birth in a year: This is collected only for mature cattle, buffalo, and sheep.

- Number of off-spring produced per year: This is relevant to female livestock that have multiple births per year (e.g., ewes).

- Feed digestibility (DE%): The portion of gross energy (GE) in the feed not excreted in the faeces is known as digestible feed. The feed digestibility is commonly expressed as a percentage (%) of GE or TDN (total digestible nutrients). That percentage of feed that is not digested represents the % of dry matter intake that will be excreted as faeces. Typical digestibility values for a range of livestock classes and diet types are presented in Table 4 as a guideline. For ruminants, common ranges of feed digestibility are 45-55% for crop by-products and range lands; 55-75% for good pastures, good preserved forages, and grain supplemented forage-based diets; and 75-85% for grain-based diets fed in feedlots.

Variations in diet digestibility results in major variations in the estimate of feed needed to meet animal requirements and consequently associated methane emissions and amounts of manure excreted. It is also important to note that digestibility, intake, and growth are co-dependent phenomena. For example, a low digestibility will lead to lower feed intake and consequently reduced growth. Conversely, feeds with high digestibility will often result in a higher feed intake and increased growth. A 10% error in estimating DE will be magnified to 12 to 20% when estimating methane emissions and even more (20 to 45%) for manure excretion (volatile solids). Digestibility data should be based on measured values for the dominant feeds or forages being consumed by livestock with consideration for seasonal variation. In general, the digestibility of forages decreases with increasing maturity and is typically lowest during the dry season. Due to significant variation, digestibility coefficients should be obtained from local scientific data wherever possible. The concentration of crude protein in the feed can be used in the process of estimating nitrogen excretion.

Average annual wool production per sheep (kg yr^{-1}):

The amount of wool produced in kilograms (after drying out but before scouring or other chemical treatment) is needed to estimate the amount of energy allocated for wool production.

Gross energy calculations

Animal performance and diet data are used to estimate feed intake, which is the amount of energy (MJ/day) an animal needs for maintenance and for activities such as growth, lactation, and pregnancy. For inventory compilers who have well-documented and recognized country-specific methods for estimating intake based on animal performance data, it is good practice to use the country-specific methods. The following section provides methods for estimating gross energy intake for the key ruminant categories of cattle, buffalo and sheep.

Net energy for maintenance:

(NE_m) is the net energy required for maintenance, which is the amount of energy needed to keep the animal in equilibrium where body energy is neither gained nor lost.

$$NE_m = Cf_i \cdot (Weight)^{0.75}$$

Equation 4.14 (Adapted Eq. 10.3 IPCC 2006, Ch. 10)
Net energy for maintenance

Where:

NE_m = net energy required by the animal for maintenance, MJ day^{-1}

Cf_i = a coefficient which varies for each animal category as shown in Table 4 (Coefficients for calculating NE_m), MJ day^{-1} kg^{-1}

Weight = live-weight of animal, kg

Table A2.4 | Coefficients for calculating net energy for maintenance (NEM). Adapted from Table 10.4, IPCC, 2006, Ch 10.

Animal category	Cf_i (MJ d^{-1} kg^{-1})	Comments
Cattle/Buffalo (non-lactating cows)	0.322	
Cattle/Buffalo (lactating cows)	0.386	This value is 20% higher for maintenance during lactation
Cattle/Buffalo (bulls)	0.370	This value is 15% higher for maintenance of intact males
Sheep (lamb to 1 year)	0.236	This value can be increased by 15% for intact males
Sheep (older than 1 year)	0,217	This value can be increased by 15% for intact males.

Net energy for activity:

(NE_a) is the net energy for activity, or the energy needed for animals to obtain their food, water and shelter. It is based on its feeding situation rather than characteristics of the feed itself. The equation for estimating NE_a for cattle and buffalo is different from the equation used for sheep. Both equations are empirical with different definitions for the coefficient C_a.

Where:

NE_a = net energy for animal activity, MJ day^{-1}

C_a = coefficient corresponding to animal's feeding situation (Table 6, Activity coefficients)

NE_m = net energy required by the animal for maintenance (Equation 3.1), MJ day^{-1}

$$NE_a = C_a \cdot NE_m$$

Equation 4.14b (Adapted Eq. 10.4 IPCC 2006, Ch. 10)
Net energy for activity (for cattle and buffalo)

Where:

NE_a = net energy for animal activity, MJ day^{-1}

C_a = coefficient corresponding to animal's feeding situation (Table 6), MJ day^{-1} kg^{-1}

Weight = live-weight of animal, kg

For Equations 4.13 and 4.14, the coefficient C_a corresponds to a representative animal's feeding situation as described earlier. Values for C_a are shown in Table 5. If a mixture of these feeding situations occurs during the year, NE_a must be weighted accordingly

Table 5 | Activity coefficients corresponding to animal's feeding situation. Adapted from Table 10.5, IPCC, 2006, Ch 10.

Situation	Definition	C_a
Cattle and Buffalo (unit for C_a is dimensionless)		
Stall	Animals are confined to a small area (i.e., tethered, pen, barn) with the result that they expend very little or no 0.00 energy to acquire feed.	0,00
Pasture	Animals are confined in areas with sufficient forage 0.17 requiring modest energy expense to acquire feed.	0,17
Grazing large areas	Animals graze in open range land or hilly terrain and expend significant energy to acquire feed.	0.36
Sheep (unit for Ca = MJ d^{-1} kg^{-1})		
Housed ewes	Animals are confined due to pregnancy in final trimester (50 days).	0.0090
Grazing flat pasture	Animals walk up to 1000 meters per day and expend very little energy to acquire feed.	0.0107
Grazing hilly pasture	Animals walk up to 5,000 meters per day and expend significant energy to acquire feed.	0.0240
Housed fattening lambs	Animals are housed for fattening.	0.0067

Net energy for growth:

(NE_g) is the net energy needed for growth (i.e., weight gain) that are calculated by Equations 4.15 and 4.16. Constants for conversion from calories to joules and live to shrunk and empty body weight have been incorporated into the equation.

$$NE_a = C_a \bullet (weight)$$

Equation 4.15 (Adapted Eq. 10.5 IPCC 2006, Ch. 10)
Net energy for activity (for sheep)

Where:

NE_g = net energy needed for growth, MJ day^{-1}

BW = the average live body weight (BW) of the animals in the population, kg

C = a coefficient with a value of 0.8 for females, 1.0 for castrates and 1.2 for bulls

MW = the mature live body weight of an adult animal in moderate body condition, kg

WG = the average daily weight gain of the animals in the population, kg day^{-1}

$$NE_g = 22{,}02 \bullet (BW / C \bullet MW)^{0.75} \bullet WG^{1.097}$$

Equation 4.16 (Adapted Eq. 10.6 IPCC 2006, Ch. 10)
Net energy for growth (for cattle and buffalo)

Where:

NE_g = net energy needed for growth, MJ day^{-1}

WG_{lamb} = the weight gain (BW_f – BW_i), kg yr^{-1}

BW_i = the live body weight at weaning, kg

BW_f = the live body weight at 1-year old or at slaughter (live-weight) if slaughtered prior to 1 year of age, kg

a, b = constants as described in Table A2.6

Table 6 | Constants for use in calculating NE_g for sheep. Adapted from Table 10.6, IPCC, 2006, Ch 10.

Animal species/category	a (MJ kg^{-1})	b (MJ kg^{-2})
Intact males	2,5	0,35
Castrates	4,4	0,32
Females	2,1	0,45

$$NE_g = \frac{WG_{lamb} \bullet \left(a + 0.5b\left(BW_i + BW_f\right)\right)}{365}$$

Equation 4.17 (Adapted Eq. 10.7 IPCC 2006, Ch. 10)
Net energy for growth (for sheep)

Net energy for lactation:

(NE_l) is the net energy for lactation. For cattle and buffalo the net energy for lactation is expressed as a function of the amount of milk produced and its fat content expressed as a percentage (e.g., 4%).

$$NE_l = Milk \bullet (1.47 + 0.40 \bullet Fat)$$

Equation 4.18 (Adapted Eq. 10.8 IPCC 2006, Ch. 10)
Net energy for lactation (for beef cattle, dairy cattle and buffalo)

Where:

NE_l = net energy for lactation, MJ day^{-1}

Milk = amount of milk produced, kg of milk day^{-1}

Fat = fat content of milk, % by weight.

Two methods for estimating the net energy required for lactation (NE_l) are presented for sheep. The first method (Equation 4.19) is used when the amount of milk produced is known, and the second method (Equation 4.20) is used when the amount of milk produced is not known. Generally, milk production is known for ewes kept for commercial milk production, but it is not known for ewes that suckle their young to weaning. With a known amount

of milk production, the total annual milk production is divided by 365 days to estimate the average daily milk production in kg/day (Equation 4.20). When milk production is not known, it is indicated that for a single birth, the milk yield is about 5 times the weight gain of the lamb. For multiple births, the total annual milk production can be estimated as five times the increase in combined weight gain of all lambs birthed by a single ewe. The daily average milk production is estimated by dividing the resulting estimate by 365 days as shown in Equation 3.8.

$$NE_l = Milk \bullet EV_{milk}$$

Equation 4.19 (Adapted Eq. 10.9 IPCC 2006, Ch. 10)
Net energy for lactation for sheep (milk production known)

Where:

NE_l = net energy for lactation, MJ day^{-1}

Milk = amount of milk produced, kg of milk day^{-1}

EV_{milk} = the net energy required to produce 1 kg of milk. A default value of 4.6 MJ/kg can be

used which corresponds to a milk fat content of 7% by weight

$$NE_l = \left[\frac{(5 \bullet WG_{wean})}{365}\right] \bullet EV_{milk}$$

Equation 4.20 (Adapted Eq. 10.10 IPCC 2006, Ch. 10)
Net energy for lactation for sheep (milk production unknown)

Where:

NE_l = net energy for lactation, MJ day^{-1}

WG_{wean} = the weight gain of the lamb between birth and weaning, kg

EV_{milk} = the energy required to produce 1 kg of milk, MJ kg^{-1}. A default value of 4.6 MJ kg^{-1} can be used.

Net energy for work:

(NE_{work}) is the net energy for work. It is used to estimate the energy required for draft power for cattle and buffalo. The strenuousness of the work performed by the animal influences the energy requirements, and consequently a wide range of energy requirements have been estimated. About 10 percent of a day's NE_m requirements are required per hour for typical work for draft animals. This value is used as follows:

$$NE_{work} = 0.10 \bullet NE_m \bullet Hours$$

Equation 4.21 (Adapted Eq. 10.11 IPCC 2006, Ch. 10)
Net energy for work (for cattle and buffalo)

Where:

NE_{work} = net energy for work, MJ day^{-1}

NE_m = net energy required by the animal for maintenance (Equation 4.1), MJ day^{-1}

Hours = number of hours of work per day

Net energy for wool production:

(NE_{wool}) is the average daily net energy required for sheep to produce a year of wool. The NE_{wool} is calculated as follows:

$$NE_{wool} = \left(\frac{EV_{wool} \bullet Production_{wool}}{365}\right)$$

Equation 4.22 (Adapted Eq. 10.12 IPCC 2006, Ch. 10)
Net energy to produce wool (for sheep)

Where:

NE_{wool} = net energy required to produce wool, MJ day^{-1}

EV_{wool} = the energy value of each kg of wool produced (weighed after drying but before scouring), MJ kg^{-1}. A default value of 24 MJ kg^{-1} can be used for this estimate.

$Production_{wool}$ = annual wool production per sheep, kg yr^{-1}

Net energy for pregnancy:

(NE_p) is the energy required for pregnancy. For cattle and buffalo, the total energy requirement for pregnancy for a 281-day gestation period averaged over an entire year is calculated as 10% of NE_m. For sheep, the NE_p requirement is similarly estimated for the 147-day gestation period, although the percentage varies with the number of lambs born (Table 8, Constant for Use in Calculating NE_p in Equation 4.23). Equation 4.23 shows how these estimates are applied.

$$NE_p = C_{pregnancy} \bullet NE_m$$

Equation 4.23 (Adapted Eq. 10.13 IPCC 2006, Ch. 10)
Net energy for pregnancy (for cattle/buffalo and sheep)

Where:

NE_p = net energy required for pregnancy, MJ day^{-1}

$C_{pregnancy}$ = pregnancy coefficient (see Table 7)

NE_m = net energy required by the animal for maintenance (Equation 4.1), MJ day^{-1}

Table 7 | Constants for use in calculating NE_p in equation 3.11. Adapted from Table 10.7, IPCC, 2006, Ch 10.

Animal category	$C_{pregnancy}$
Cattle and Buffalo	0,10
Sheep	
Single birth	0,077
Double birth (twins)	0,126
Triple birth or more (triplets)	0,150

When using NE_p to calculate GE for cattle and sheep, the NE_p estimate must be weighted by the portion of the mature females that go through gestation in a year. For example, if 80% of the mature females in the animal category give birth in a year, then 80% of the NE_p value would be used in the GE equation below.

To determine the proper coefficient for sheep, the portion of ewes that have single births, double births, and triple births is needed to estimate an average value for $C_{pregnancy}$. If these data are not available, the coefficient can be calculated as follows:

• If the number of lambs born in a year divided by the number of ewes that are pregnant in a year is less than or equal to 1.0, then the coefficient for single births can be used.

• If the number of lambs born in a year divided by the number of ewes that are pregnant in a year exceeds 1.0 and is less than 2.0, calculate the coefficient as follows:

$C_{pregnancy}$ = [(0.126 • Double birth fraction) + (0.077 . Single birth fraction)] (Equation 4.24)

Where:

Double birth fraction = [(lambs born / pregnant ewes) – 1]

Single birth fraction = [1 – Double birth fraction]

Ratio of net energy available in diet for maintenance to digestible energy consumed (R_{EM}):

For cattle, buffalo and sheep, the ratio of net energy available in a diet for maintenance to digestible energy consumed (R_{EM}) is estimated using the following equation:

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_1 + NE_{work} + NE_p}{REM} \right) + \left(\frac{NE_g + NE_{wool}}{REG} \right)}{\frac{DE\%}{100}} \right]$$

Equation 4.24 (Adapted Eq. 10.14 IPCC 2006, Ch. 10)
Ratio of net energy available in a diet for maintenance to digestible energy consumed

Where:

REM = ratio of net energy available in a diet for maintenance to digestible energy consumed.

DE% = digestible energy expressed as a percentage of gross energy

Ratio of net energy available for growth in a diet to digestible energy consumed (REG):

For cattle, buffalo and sheep the ratio of net energy available for growth (including wool growth) in a diet to digestible energy consumed (REG) is estimated using the following equation:

$$REG = \left[1.164 - \left(5.160 \bullet 10^{-3} \bullet DE\%\right) + \left[1.308 \bullet 10^{-5} \bullet (DE\%)^2\right] - \left(\frac{37.4}{DE\%}\right)\right]$$

Equation 4.25 (Adapted Eq. 10.15 IPCC 2006, Ch. 10)
Ratio of net energy available for growth in a diet to digestible energy consumed

Where:

REG = ratio of net energy available for growth in a diet to digestible energy consumed

DE% = digestible energy expressed as a percentage of gross energy

Gross energy, GE:

As shown in Equation 4.26, GE requirement is derived based on the summed net energy requirements and the energy availability characteristics of the feed(s). Equation 3.14 represents good practice for calculating GE requirements for cattle and sheep using the results of the equations presented above. In using Equation 4.26, only those terms relevant to each animal category are used.

$$REM = \left[1.123 - \left(4.092 \bullet 10^{-3} \bullet DE\%\right) + \left[1.126 \bullet 10^{-5} \bullet (DE\%)^2\right] - \left(\frac{25.4}{DE\%}\right)\right]$$

Equation 4.26 (Adapted Eq. 10.16 IPCC 2006, Ch. 10)
Gross energy for cattle/buffalo and sheep

where:

GE = gross energy, MJ day^{-1}

NE_m = net energy required by the animal for maintenance, (Equation 4.1), MJ day^{-1}

NE_a = net energy for animal activity, (Equations 4.2 and 4.3), MJ day^{-1}

NE_l = net energy for lactation, (Equations 4.6, 4.7 and 4.8), MJ day^{-1}

NE_{work} = net energy for work (Equation 4.9), MJ day^{-1}

NE_p = net energy required for pregnancy (Equation 4.11), MJ day^{-1}

REM = ratio of net energy available in a diet for maintenance to digestible energy consumed (Equation 4.12)

NE_g = net energy needed for growth (Equations 4.4 and 4.5), MJ day^{-1}

NE_{wool} = net energy required to produce a year of wool (Equation 4.10), MJ day^{-1}

REG = ratio of net energy available for growth in a diet to digestible energy consumed (Equation 4.13) DE%= digestible energy expressed as a percentage of gross energy

Once the values for GE are calculated for each animal subcategory, the feed intake in units of kilograms of dry matter per day (kg day^{-1}) should also be calculated. To convert from GE in energy units to dry matter intake (DMI), divide GE by the energy density of the feed. A default value of 18.45 MJ kg^{-1} of dry matter can be used if feed-specific information is not available. The resulting daily dry matter intake should be in the order of 2% to 3% of the body weight of the mature or growing animals. In high producing milk cows, intakes may exceed 4% of body weight.

Feed intake estimates using a simplified Tier 2 method:

Prediction of DMI for cattle based on body weight and estimated dietary net energy concentration (NE_{ma}) or digestible energy values (DE%):

It is also possible to predict dry matter intake for mature and growing cattle based on body weight of the animal and either the NE_{ma} concentration of the feed or DE%. Dietary NE_{ma} concentration can range from 3.0 to 9.0 MJ kg^{-1} of dry matter. Typical values for high, moderate and low-quality diets are presented in Table 8. These figures can also be used to estimate NEma values for mixed diets based on an estimate of diet quality. For example, a mixed forage-grain diet could be assumed to

have a NEma value like that of a high-quality forage diet. A mixed grain-straw diet could be assumed to have a NEma value like that of a moderate quality forage. Nutritionists within specific geographical areas should be able to provide advice regarding the selection of NEma values that are more representative of locally fed diets. Dry matter intake for growing and finishing cattle is estimated using the following equation:

$$DMI = BW^{0.75} \bullet \left[\frac{\left(0.2444 \bullet NE_{ma} - 0.0111 \bullet NE_{ma}^{\ 2} - 0.472\right)}{NE_{ma}} \right]$$

Equation 4.27 (Adapted Eq. 10.17 IPCC 2006, Ch. 10)
Estimation of dry matter intake for growing and finishing cattle

Where:

DMI = dry matter intake, kg day^{-1}

BW = live body weight, kg

NE_{ma} = estimated dietary net energy concentration of diet or default values in Table 8, MJ kg^{-1}

Dry matter intake for mature beef cattle is estimated using the following equation:

$$DMI = BW^{0.75} \bullet \left[\frac{\left(0.0119 \bullet NE_{ma}^{\ 2} + 0.1938\right)}{NE_{ma}} \right]$$

Equation 4.28a (Adapted Eq. 10.18a IPCC 2006, Ch. 10)
Estimation of dry matter intake for mature beef cattle

Where:

DMI = dry matter intake, kg day^{-1}

BW = live body weight, kg NE_{ma} = estimated dietary net energy concentration of diet or default values given in Table 9, MJ kg^{-1} . For mature dairy cows consuming low quality, often tropical forages, the following alternative equation for estimating dry matter intake based on DE% can be used:

$$DMI = \left[\frac{\left(\frac{(5.4 \bullet BW)}{500}\right)}{\left(\frac{(100 - DE\%)}{100}\right)} \right]$$

Equation 4.28b (Adapted Eq. 10.18b IPCC 2006, Ch. 10)
Estimation of dry matter intake for mature dairy cows

where:

DMI = dry matter intake, kg day^{-1}

BW = live body weight, kg

DE%= digestible energy expressed as a percentage of gross energy (typically 45-55% for low quality forages)

Equations 4.27, 4.28a and 4.28b provide a good check to the main Tier 2 method to predict feed intake. They can be viewed as asking 'what is an expected intake for a given diet quality?' and used to independently predict DMI from BW and diet quality (NEma or DE%). In contrast, the main Tier 2 method predicts DMI based on how much feed must be consumed to meet estimated requirements (i.e., NEm and NEg) and does not consider the biological capacity of the animal to in fact consume the predicted quantity of feed. Consequently, the simplified Tier 2 method can be used to confirm that DMI values derived from the main Tier 2 method are biologically realistic. These estimates are also subject to the cross check that dry matter intake should be in the order of 2% to 3% of the bodyweight of the mature or growing animals.

Table 8 | Examples of NE_{ma} content of typical diets fed to cattle for estimation of dry matter intake in equations 3.15 and 3.16. Adapted from Table 10.8, IPCC, 2006, Ch 10.

Diet type	NE_{ma} (MJ (kg dry matter)$^{-1}$)
High grain diet > 90%	7.5 - 8.5
High quality forage (e.g., vegetative legumes & grasses)	6.5 - 7.5
Moderate quality forage (e.g., mid season legume & grasses)	5.5 - 6.5
Low quality forage (e.g., straws, mature grasses)	3.5 - 5.5

Source: Estimates obtained from predictive models in NRC (1996), NE_{ma} can also be estimated using the equation: NE_{ma} = REM x 18.45 x DE% / 100.

A2.4 Methane emissions from enteric fermentation

Methane is produced in herbivores as a by-product of enteric fermentation, a digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream. The amount of methane that is released depends on the type of digestive tract, age, and weight of the animal, and the quality and quantity of the feed consumed. Ruminant livestock (e.g., cattle and sheep) are major sources of methane with moderate amounts produced from non-ruminant livestock (e.g., pigs and horses). The ruminant gut structure fosters extensive enteric fermentation of their diet.

Digestive system

The type of digestive system has a significant influence on the rate of methane emission. Ruminant livestock have an expansive chamber, the rumen, at the fore part of their digestive tract that supports intensive microbial fermentation of their diet which yields several nutritional advantages including the capacity to digest cellulose in their diet. The main ruminant livestock are cattle, buffalo, goats, sheep, deer and camelids. Non-ruminant livestock (horses, mules, asses) and monogastric livestock (swine) have relatively lower methane emissions because much less methane-producing fermentation takes place in their digestive systems.

Feed intake

Methane is produced by the fermentation of feed within the animal's digestive system. Generally, the higher the feed intake, the higher the methane emission. Although, the extent of methane production may also be affected by the composition of the diet. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, or pregnancy). To reflect the variation in emission rates among animal species, the population of animals should be divided into subgroups, and an emission rate per animal is estimated for each subgroup. Types of population subgroups are provided in Section 10.2 (Livestock and feed characterization). The amount of methane emitted by a population subgroup is calculated by multiplying the emission rate per animal by the number of animals within the subgroup. Natural wild ruminants are not considered in the derivation of a country's emission estimate. Emissions should only be considered from animals under domestic management (e.g., farmed deer, elk, and buffalo).

Choice of method

The method for estimating methane emission from enteric fermentation requires three basic steps:

Step 1:

Divide the livestock population into subgroups and characterize each subgroup as described previously. It is recommended that national experts use annual averages estimated with consideration for the impact of production cycles and seasonal influences on population numbers.

Step 2:

Estimate emission factors for each subgroup in terms of kilograms of methane per animal per year.

Step 3: Multiply the subgroup emission factors by the subgroup populations to estimate subgroup emission, and sum across the subgroups to estimate total emission.

These three steps can be performed at varying levels of detail and complexity.

Tier 1

A simplified approach that relies on default emission factors either drawn from the literature or calculated using the more detailed Tier 2 methodology. The Tier 1 method is likely to be suitable for most animal species in farms where enteric fermentation is not a key source category, or where enhanced characterization data are not available. When approximate enteric emissions are derived by extrapolation from main livestock categories, they should be a Tier 1 method.

Tier 2

A more complex approach that requires detailed country-specific data on gross energy intake and methane conversion factors for specific livestock categories. The Tier 2 method should be used if enteric fermentation is a key source category for the animal category that represents a large portion of the farm's total emissions.

Tier 3

Some countries for which livestock emissions are particularly important may wish to go beyond the Tier 2 method and incorporate additional country-specific information in their estimates. This approach could employ the development of sophisticated models that consider diet composition in detail, concentration of products arising from ruminant fermentation, seasonal variation in animal population or feed quality and availability, and possible mitigation strategies. Many of these estimates would be derived from direct experimental measurements. A Tier 3 method should be subjected to a wide degree of international peer review such as that which occurs in peer-reviewed publications to ensure that they improve the accuracy and / or precision of estimates.

Tier 1

Table 9 summarizes the suggested approaches for the livestock emissions included in this inventory.

Table 9 | Suggested emissions inventory methods for enteric fermentation. Adapted from Table 10.9, IPCC, 2006, Ch 10.

Livestock	Suggested emissions inventory methods
Dairy Cow	Tier 2/Tier 3
Other Cattle	Tier 2/Tier 3
Buffalo	Tier 1/Tier 2
Sheep	Tier 1/Tier 2
Goats	Tier 1
Camels	Tier 1
Horses	Tier 1
Mules and Asses	Tier 1
Other (e.g., Llamas, Alpacas, Deer)	Tier 1

Table 10 shows the enteric fermentation emission factors for each of the animal species except cattle. As shown in the table, emission factors for sheep vary for developed and developing countries. The differences in the emission factors are driven by differences in feed intake and feed characteristic assumptions. Table 11 presents the enteric fermentation emission factors for cattle. A range of emission factors is shown for typical regional conditions. As shown in the table, the emission factors vary by over a factor of four on a per head basis.

While the default emission factors shown in Table 11 are broadly representative of the emission rates within each of the regions described, emission factors vary within each region. Animal size and milk production are important determinants of emission rates for dairy cows. Relatively smaller dairy cows with low levels of production are found in Asia, Africa, and the Indian subcontinent. Relatively larger dairy cows with high levels of production are found in North America and Western Europe.

Animal size and population structure are important determinants of emission rates for other cattle. Relatively smaller other cattle are found in Asia, Africa, and the Indian subcontinent. Also, many of the other cattle in these regions are young. Other cattle in North America, Western Europe and Oceania are larger, and young cattle constitute a smaller portion of the population. To select emission factors from Tables 10 and 11, identify the region most applicable to the country/farm being evaluated.

The data collected on the average annual milk production by dairy cows should be used to help select a dairy cow emission factor. If necessary, interpolate between dairy cow emission factors shown in the table using the data collected on average annual milk production per head.

Table 10 | Enteric fermentation emission factors for tier 1 method1 (kg CH_4 $head^{-1}$ yr^{-1}). Adapted from Table 10.10, IPCC, 2006, Ch 10.

Livestock	Developed countries	Developing countries	Liveweight
Buffalo	55	55	300 kg
Sheep	8	5	65 kg - developed countries; 45 kg - developing countries
Goats	5	5	40 kg
Camels	46		570kg
Horses	18	18	550 kg
Mules and Asses	10	10	245 kg
Deer	20	20	120kg
Alpacas	8	8	65 kg

Step 3:

Total emission

To estimate total emission, the selected emission factors are multiplied by the associated animal population (Equation 4.29) and summed (Equation 4.30):

$$Emissions = EF_{(T)} \bullet \left(\frac{N_{(T)}}{10^6} \right)$$

Equation 4.29 (Adapted Eq. 10.19 IPCC 2006, Ch. 10) Enteric fermentation emissions from a livestock category

Where:

Emissions = methane emissions from Enteric Fermentation, Gg CH_4 yr^{-1}

$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4 $head^{-1}$ yr^{-1}

$N_{(T)}$ = the number of head of livestock species / category T in the country T = species/category of livestock

$$\text{Total } CH_{4\text{Enteric}} = \sum_i E_i$$

Equation 4.30 (Adapted Eq. 10.20 IPCC 2006, Ch. 10) Enteric fermentation emissions from a livestock category

Where:

Total $CH_{4Enteric}$ = total methane emissions from Enteric Fermentation, Gg CH_4 yr^{-1}

E_i = is the emissions for the i^{th} livestock categories and subcategories

Table 11 | Tier 1 enteric fermentation emission factors for cattle. Adapted from Table 10.11, IPCC, 2006, Ch 10.

Regional characteristics	Cattle category	Emission factor (kg CH_4 $head^{-1}$ yr^{-1})	Comments
North America: Highly productive commercialized dairy sector feeding high quality forage and grain. Separate beef cow herd, primarily grazing with feed supplements seasonally. Fast-growing beef steers/ heifers finished in feedlots on grain. Dairy cows are a small part of the population.	Dairy	128	Average milk production of 8,400 kg $head^{-1}$ yr^{-1}
	Other Cattle	53	Includes beef cows, bulls, calves, growing steers/heifers, and feedlot cattle.
Western Europe: Highly productive commercialised dairy sector feeding high quality forage and grain. Dairy cows also used for beef calf production. Very small dedicated beef cow herd. Minor amount of feedlot feeding with grains.	Dairy	117	Average milk production of 6,000 kg $head^{-1}$ yr^{-1} .
	Other Cattle	57	Includes bulls, calves, and growing steers/heifers.
Eastern Europe: Commercialised dairy sector feeding mostly forages. Separate beef cow herd, primarily grazing. Minor amount of feedlot feeding with grains.	Dairy	99	Average milk production of 2,550 kg $head^{-1}$ yr^{-1}.
	Other Cattle	58	Includes beef cows, bulls, and young.
Oceania: Commercialised dairy sector based on grazing. Separate beef cow herd, primarily grazing rangelands of widely varying quality. Growing amount of feedlot feeding with grains. Dairy cows are a small part of the population.	Dairy	90	Average milk production of 2,200 kg $head^{-1}$ yr^{-1}.
	Other Cattle	60	Includes beef cows, bulls, and young.
Latin America: Commercialised dairy sector based on grazing. Separate beef cow herd grazing pastures and rangelands. Minor amount of feedlot feeding with grains. Growing non-dairy cattle comprise a large portion of the population.	Dairy	72	Average milk production of 800 kg $head^{-1}$ yr^{-1}.
	Other Cattle	56	Includes beef cows, bulls, and young.
Asia: Small commercialised dairy sector. Most cattle are multi-purpose, providing draft power and some milk within farming regions. Small grazing population. Cattle of all types are smaller than those found in most other regions.	Dairy	68	Average milk production of 1,650 kg $head^{-1}$ yr^{-1}.
	Other Cattle	47	Includes multi-purpose cows, bulls, and young
Africa and Middle East: Commercialised dairy sector based on grazing with low production per cow. Most cattle are multi-purpose, providing draft power and some milk within farming regions. Some cattle graze over very large areas. Cattle are smaller than those found in most other regions.	Dairy	46	Average milk production of 475 kg $head^{-1}$ yr^{-1}.
	Other Cattle	31	Includes multi-purpose cows, bulls, and young
Indian Subcontinent: Commercialised dairy sector based on crop by-product feeding with low production per cow. Most bullocks provide draft power and cows provide some milk in farming regions. Small grazing population. Cattle in this region are the smallest compared to cattle found in all other regions.	Dairy	58	Average milk production of 900 kg $head^{-1}$ yr^{-1}.
	Other Cattle	27	Includes cows, bulls, and young. Young comprise a large portion of the population

Tier 2

Approach for methane emissions from Enteric Fermentation

The Tier 2 method is applied to more disaggregated livestock population categories and used to calculate emission factors, as opposed to default values. The key considerations for the Tier 2 method are the development of emission factors and the collection of detailed activity data.

Step 1: Livestock population

The animal population data and related activity data should be obtained following the approach described previously.

Step 2: Emission factors

When the Tier 2 method is used, emission factors are estimated for each animal category using the detailed data developed in Step 1. The emission factors for each category of livestock are estimated based on the gross energy intake and methane conversion factor for the category. The gross energy intake data should be obtained using the approach described previously. The following two sub-steps need to be completed to calculate the emission factor under the Tier 2 method:

Obtaining the methane conversion factor (Y_m) The extent to which feed energy is converted to CH_4 depends on several interacting feed and animal factors. If CH_4 conversion factors are unavailable from country-specific research, the values provided in Table 12, Cattle/Buffalo CH_4 conversion factors, can be used for cattle and buffalo. These general estimates are a rough guide based on the general feed characteristics and production practices found in many developed and developing countries. When good feed is available (i.e., high digestibility and high energy value) the lower bounds should be used. When poorer feed is available, the higher bounds are more appropriate. A CH_4 conversion factor of zero is assumed for all juveniles consuming only milk (i.e., milk-fed lambs as well as calves).

Due to the importance of Y_m in driving emissions, substantial ongoing research is aimed at improving estimates of Y_m for different livestock and feed combinations. Such improvement is most needed for animals fed on tropical pastures as the available data are sparse. For example, a recent study observed Y_m values outside the ranges described in Table 13.

Table 12 | Cattle/buffalo CH_4 conversion factors (Y_m). Adapted from Table 10.12, IPCC, 2006, Ch 10.

Livestock category	Y_m [b]
Feedlot fed Cattle	3.0% +/- 1.0%
Dairy Cows (Cattle and Buffalo) and their young	6.5% +/- 1.0%
Other Cattle and Buffaloes that are primarily fed low quality crop residues and by- products	6.5% +/- 1.0%
Other Cattle or Buffalo – grazing	6.5% +/- 1.0%

Table 13 proposes a common Y_m value for all mature sheep irrespective of feed quality, but with different values for mature and juvenile sheep with demarcation at 1 year of age. The median value is appropriate for most applications, but for poor quality feed the upper limits may be more appropriate, and for high-digestibility high-energy feeds the lower limits may be used.

Table 13 | Sheep CH_4 conversion factors (Y_m). Adapted from Table 10.13, IPCC, 2006, Ch 10.

Category	Y_m [a]
Lambs (<1 year old)	4.5% + 1.0%
Mature Sheep	6.5% + 1.0%

$$\text{Total } CH_{4\text{Enteric}} = \sum_i E_i$$

Equation 4.31 (Adapted Eq. 10.20 IPCC 2006, Ch. 10)
Total emissions from livestock enteric fermentation

Note that in some cases, CH_4 conversion factors may not exist for specific livestock types. In these instances, CH_4 conversion factors from the reported livestock that most closely resembles those livestock types can be reported. For example, CH_4 conversion factors for other cattle or buffalo could be applied to estimate an emission factor for camels. 2. Emission factor development An emission factor for each animal category should be developed following Equation 4.32:

$$EF = \left[\frac{GE \bullet \left(\frac{Y_m}{100} \right) \bullet 365}{55.65} \right]$$

Equation 4.32 (Adapted Eq. 10.21 IPCC 2006, Ch. 10)
CH_4 emission factors for enteric fermentation from a livestock category

where:

EF = emission factor, kg CH_4 $head^{-1}$ yr^{-1}

GE = gross energy intake, MJ $head^{-1}$ day^{-1}

Y_m = methane conversion factor, percent of gross energy in feed converted to methane

The factor 55.65 (MJ/kg CH_4) is the energy content of methane

This emission factor equation assumes that the emission factors are being developed for an animal category for an entire year (365 days). While a full year emission factor is typically used, in some circumstances the animal category may be defined for a shorter period (for example, for the wet season of the year or for a 150-day feedlot feeding period). In this case, the emission factor would be estimated for the specific period (for example, the wet season) and the 365 days would be replaced by the number of days in the period.

Step 3:

Total emissions

To estimate total emissions, the selected emission factors are multiplied by the associated animal population and summed. As described above under Tier 1, the emissions estimates should be reported in gigagrams (Gg).

Choice of activity data

Livestock population data should be obtained using the approach described previously. If using default enteric emission factors for livestock (Tables 11 and 12) to estimate enteric emissions, a basic (Tier 1) livestock population characterization is enough. To estimate enteric emissions from livestock using estimation of Gross Energy Intake (Equations 3.14, 3.15 and 3.16), a Tier 2 characterization is needed. A good practice in characterising livestock populations is to conduct a single characterization that will provide the activity data for all emissions sources that depend on livestock population data.

Pexels

Annex 3 Soil sampling sub-protocol

The soil sampling subprotocol provides instructions for implementing a simple and feasible yet rigorous soil sampling design. A soil sampling plan including a sampling design is a key component of a measurement-based estimate of SOC as it provides instructions on how to develop a sampling plan for a project – in other words, where to take the soil samples. The purpose of the sampling plan is to detect changes in SOC over time while minimizing sampling costs. The sampling designs provided in this document are: stratified simple random sampling with compositing across strata; and stratified directed sampling with compositing for each stratum.

A3.1 Soil sampling plan

A3.1.1 Pre-sampling (from FAO, 2019a)

To analyse spatial variability of SOC stocks, a pre-sampling (5 to 10 cores) of the area of interest may be undertaken to get an indication of the SOC stocks mean value and variability in SOC stocks and, therefore, attainable minimum detectable difference (MDD) for a given sampling effort. This information should be used to guide estimation of the number of samples needed to determine SOC stock change with an acceptable level of uncertainty. Power analysis can be conducted a priori, given a certain variance and α-level (i.e. significance level). The MDD for paired observations is calculated as following:

$$MDD \geq \frac{S}{\sqrt{n}} \cdot (t_{\alpha,v} + t_{\beta,v})$$ **Equation A3.1**

where, S is the standard deviation of the difference in SOC stocks between to and t1, n is the number of replicates, v = n – 1 represents the degrees of freedom for the relevant t-distribution, t are the values of the t-distribution given a certain power level (1-β) and α level.

Thus, the minimum number of samples required to detect an expected difference between two successive sampling rounds can then be determined as:

$$n \geq \left(\frac{S \cdot (t_{\alpha} + t_{\beta})}{MDD} \right)^2$$ **Equation A3.2**

where n is the number of samples, S is the estimated standard deviation, MDD is the minimum detectable difference tα is the two-sided critical value of the t-distribution at a given significance level (α) (frequently taken as 5 to 10%; 0.05-0.1), and tβ is the one-sided quartile of the t-distribution corresponding to a probability of type II error β (being 1 - β the statistical power ; frequently 80 to 90%).

A3.1.2 Sampling over time

As explained in Section 8, the first round of sampling is used to establish the baseline SOC (year 0). Second and subsequent sampling rounds (every 4 years) are used to determine changes in SOC over time in the IS. In second and subsequent sampling rounds, the original sampling locations can be offset by a small distance or new random sampling locations can be selected, depending upon preference.

A3.2 Sampling design: stratified simple random sampling and directed stratified sampling designs

The Project Area is divided into one or more Intervention Areas (IAs). There are no constraints on the size of an IA; it can be any size. If there is no previous information on the IAs internal variability, each IA is divided into equal areas (strata) (Figure A3.1). A sampling location to extract a soil core is randomly allocated within each stratum to form a composite sample in the sampling plan. This approach is called **stratified simple random sampling**. It ensures that samples are taken from each part of the IA, which is a very good design for getting an estimate of SOC that is representative of SOC across the IA as a whole. A minimum of three strata must be included in each IA, but enough strata should be used to adequately sample the IA.

Sample size (=Number of composite samples): To determine the variability in the area needing to be sampled, it is recommended to take 5 to 10 composite samples in an IA before conducting the initial and successive sampling rounds (pre-sampling; Section A3.1). The number of strata and composite samples and individual taken affects the minimum change in SOC concentration that can be detected (as explained in Section A3.1). Taking more samples, particularly by increasing the number of strata, will greatly improve the ability to detect changes in SOC concentration and thereby stock over time. This protocol recommends a minimum of five composite samples for each IA, preferably more depending on budget, a minimum of 5-15 soil cores to form a composite sample, and a minimum of three strata within each IA. The number of samples in a stratum can be chosen to be proportional to its area but does not have to. In practical terms, a composite sample could be taken every 10 ha in IAs over 50 ha.

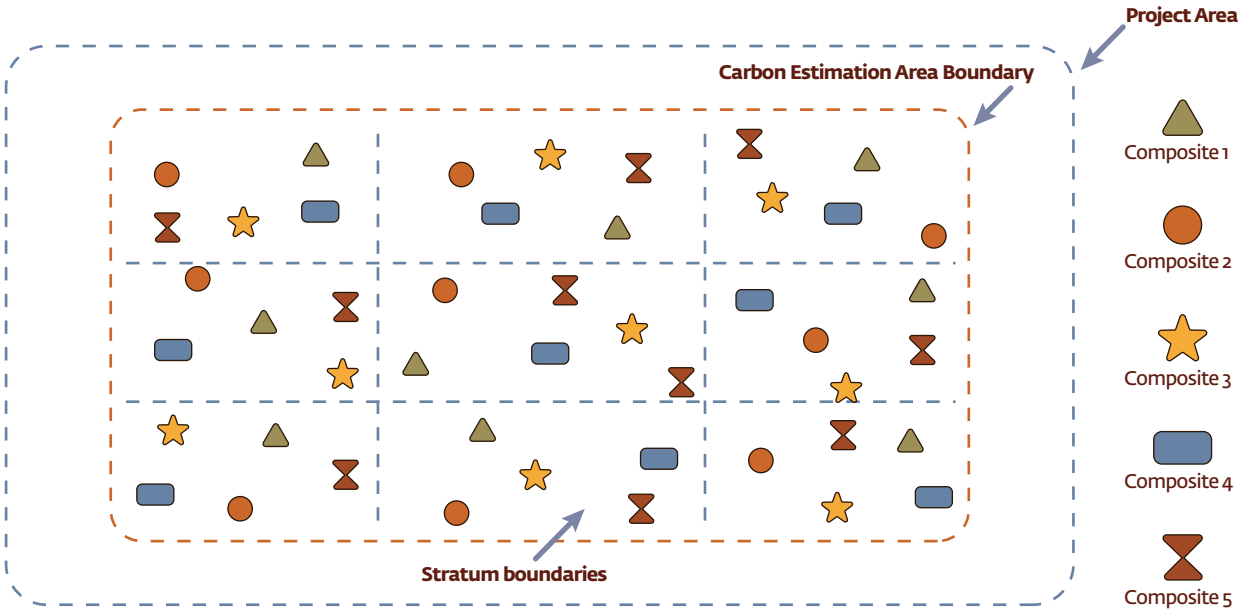

Figure A3.1 | A grid-based Intervention Area with 9 strata and sampling locations for three composites (represented by green triangles, orange circles, and yellow stars). Samples from the locations marked with each coloured symbol are combined to form one composite. Adapted from the Australian Government - Carbon Farming Initiative (2018).

If there is previous information to characterize the IA's variability (for example, from yield maps, long term average NDVI, electrical conductivity maps, altimetry maps, Figure A3.2.), each IA is divided into its corresponding strata. Sampling locations are allocated within each stratum to form composite samples. This approach is called **directed stratified sampling**. It ensures that samples are taken from each part of the different identified strata of the IA. A **minimum of three strata shall be included in each IA (Figure A3.2), but enough strata should be used to adequately sample the IA.**

Sample size (=Number of composite samples): As in the previous design, it is recommended to take 5 to 10 composite samples before conducting the initial and successive sampling rounds (pre-sampling; Section A3.1.). The number of samples in a stratum can be chosen to be proportional to its area. This protocol recommends a minimum of three composite samples per stratum (a minimum of three strata within each IA), preferably five or more composite samples depending on budget, and a minimum of 5-15 soil cores to form a composite sample. In practical terms a composite sample could be taken every 10 ha in IAs over 50 ha.

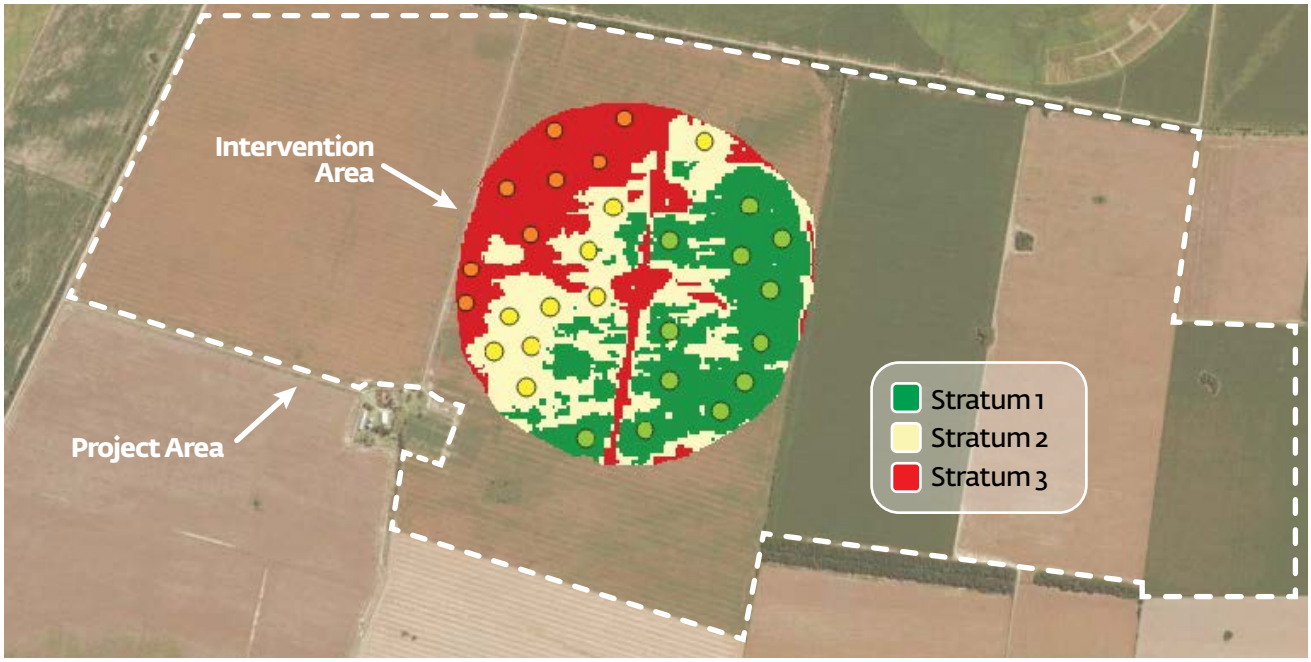

Figure A3.2 | Intervention Area with 3 strata (green: stratum 1; yellow: stratum 2; and red: stratum 3); and sampling locations to form at least 3 composites for each stratum.

Within a stratum, certain areas shall be excluded in grazed lands, such as patches with animal excreta, animal pathways, driveways to enter/leave fields, very near watering points, and sectors with intense agricultural traffic.

GPS coordinates of each sampling location shall be recorded, so that the site can always be revisited. Also, geospatial upscaling requires georeferenced SOC stock values.

A3.3 Creating composites

Compositing (or bulking) refers to the procedure of pooling together several soil cores (subsamples) into one homogeneous composite (or bulked) sample, which is then analysed for SOC content. A single soil sample shall be combined to create a composite sample (Figures A3.1 and A3.2). Each composite is analyzed for SOC content, in order to reduce the laboratory analysis costs. Compositing should be done with clean hands or gloves, using a bucket or plastic bag to homogenize the sample. If the composite sample is fully homogenized, SOC concentration should equal the average SOC concentration of individual cores (had each of them been analysed separately).

A3.4 Soil depth

Changes in SOC stocks are affected by changes in soil bulk density due to changes in soil compactness. This determines different masses for the same volume of soil. Soil carbon stocks are commonly quantified at fixed depths as the product of soil bulk density, depth and SOC concentration. However, this method systematically overestimates SOC stocks in treatments with greater bulk densities such as minimum tillage, exaggerating their benefits (Wendt and Hauser, 2013). Therefore, it is critical to report SOC stock on an equivalent soil mass basis, which should also be reported, to normalize the effects of management on bulk density (VandenBygaart and Angers, 2006).

A large amount of the organic carbon in soil is stored in the 0-5 cm and 0–10 cm layers, and this is often where differences generated by management are found. On the other hand, several authors warned about the need to obtain SOC samples below the topsoil layers, since the variations imposed by management can be detected at up to 1-metre depth or more (Blanco-Canqui and Lal, 2008; Olson and Al-Kaisi, 2015). An acceptable criterion is to reach up to 30 cm deep, separating in layers of different bulk density, as adopted for the FAO Global Soil Carbon Map (2018).

As a minimum, samples for SOC concentration determinations shall be obtained from 0-10 cm and 10-30 cm; and from 0-10 cm for POC concentration. The same 0-10 cm can be used to determine SOC and POC concentrations. Soil organic carbon stocks should be then reported for the 0–30 cm layer to comply with IPCC recommendations (IPCC, 2006; 2019); (Subprotocol A4, SOC stock estimations). However, samples from deeper layers up to 1 m can be collected, and SOC stocks estimated as explained in Annex A4. When sampling up to 1 metre, it is suggested to separate sampling depths according to different soil layers, as appropriate (e.g. 0-10, 10-30; 30-50; 50-100 cm).

A3.5 Frequency

Concerning time of sampling, soil organic carbon varies within season, so it is important to take soil samples at the same time each year (no more than a month between the median day of the different sampling rounds) and preferably when biological activity is minimum.

SOC and bulk density shall be determined as a minimum every 4 years, and POC concentration every 2 years (optional).

A3.6 Field sampling for bulk density (Section adapted from FAO, 2019a)

Soil bulk density is the dry soil mass per unit volume of the soil. For estimating bulk density, direct measurement methods shall be used, specifically the undisturbed (intact) core method and the excavation method, because these can provide the most accurate determination of bulk density compared to other methods (FAO-LEAP, 2019). The suitable sample size and method will depend on the characteristics of the coarse fraction.

A3.6.1 Intact core method

To estimate bulk density using the undisturbed (intact) core method, a known volume of soil shall be collected using a metal ring pressed into the soil (intact core), and the weight after drying shall be determined (Blake and Hartge, 1986). *This method works best for moist soils without coarse fragments.* If the soil is too dry, it is possible to wet the soil manually to keep the core intact. To do this, a bottomless drum should be placed on the soil and filled with water, allowing the soil to wet naturally for 24 hours. Then, a flat horizontal

surface should be prepared in the soil with a spade at the depth of sampling. A steel ring is pushed or gently hammered into the soil. A block of wood may be used to protect the ring. Sample compaction shall be avoided. Soil around the ring shall be excavated without disturbing or loosening the soil it contains and carefully removed with the soil intact. Any excess soil from the outside of the ring shall be removed and any plants or roots off at the soil surface shall be cut with scissors (FAO-LEAP, 2019). In the case of soils with expandable clay minerals (for example, vertisols and vertic soils), soil sample moisture content should be standardized at field capacity (-33 kPa) for BD determinations.

Sample sizes used to determine the bulk density of soils containing only or mainly fine earth are typically 100 cm^3, since coarse fragments are usually underrepresented in small samples. Thus, small samples will likely lead to sub-estimation of the bulk density of gravelly soils (see Section A3.7, Field sampling in soils with coarse fragments). Typically, core diameter should be greater than 50 mm (smaller than this, collection of coarse roots and gravel may be hampered) and less than 100 mm (larger than this, problems associated with logistics, site disruption become insurmountable). Cores with a 100 cm^3 volume (53 mm diameter, 51 mm height) are recommended by ISO 11272:2017 (Soil quality - Determination of dry bulk density). Ideally bulk density shall be estimated for the same core used to collect the sample for SOC analysis (FAO, 2019a).

A3.7 Soils with abundant coarse fragments: excavation method

This method has been found useful for loose soils, or for soils with abundant coarse fragments. Bulk density is determined by excavating a quantity of soil, drying and weighing it, and determining the volume of the excavation by filling the hole with sand of

known volume per unit mass or water (Blake and Hartge, 1986; Grossman and Reinsch, 2002; Aynekulu *et al.*, 2011). A special apparatus called sand-funnel can be used. The size of the hole will depend on the apparatus, but a larger hole approximately 12 cm in diameter) will likely result in smaller error in bulk density estimation. The depth of the hole will depend on the depth of the evaluated layer. All the excavated soil should be retained in a container to determine its dry weight as described in the undisturbed core method. (In the laboratory, the dry mass of coarse fragments > 2mm shall be estimated separately from the fine earth dry mass).

The volume of the hole should be determined by filling it up with clean, dry, free-flowing sand (standard sand with uniform particle-size 0.841-0.25 1313 mm is recommended). To estimate the soil volume a mass-to-volume ratio is used. For this reason, the mass-to-volume ratio of the sand has to be pre-calibrated by letting the sand fall from a similar height and at a similar rate of flow as in the procedure of measuring bulk density. Thus soil sample volume can be estimated using Equation A3.1:

Soil sample volume (cm^3) = Mass of the sand (g) / Density of the sand ($g\ cm^{-3}$) [Equation A3.1]

To determine the bulk density of the fine-earth fraction of soil layers that contain many coarse fragments (less than 30%), a representative field-sample volume may be smaller than 100 cm^3, but for gravelly to extremely gravelly soils (>30%) field samples between 200 and 1000 cm^3 are recommended (Vincent and Chadwick, 1994). For soils containing more than 50% coarse fragment by volume, the representative volume shall be at least 5000 cm^3.

The coarse fraction of the soil has negligible capacity to store organic carbon. Therefore, the fine earth and coarse fractions shall be separated by removing particles larger than 2 mm from the sample by wet screening (FAO-LEAP, 2019). Mass and volume of coarse fragments shall be measured separately in order to correct bulk density and adequately estimate SOC stocks (see Annex A4, SOC stock calculation subprotocol, Equations A4.1 and A4.2).

A3.8 Sample preparation and labeling (Section adapted from FAO, 2019a)

Soil samples should be collected into airtight plastic bags, and most of the air should be removed immediately after sampling. Soil samples should not be stored wet as this may quantitatively affect SOC. If drying is not possible immediately after sampling, soil samples should be stored at 4°C in the dark to reduce microbial activity, preferably for less than 28 days, as microbial degradation does not completely stop at 4°C and could lead to loss of organic materials. Freezing is not recommended. When large amounts of roots or macrofauna (e.g. earthworms) are present in the sample, it should be processed within a week, so that SOC concentration is not altered by decomposition of those components (FAO, 2019a).

Each label of composite sample should contain this legend:

- Field or farm;
- Id of Intervention Area;
- Stratum;
- GPS location;
- Date;
- Soil depth (0-10 cm) or (0-30 cm);
- Coarse element content (estimated volume %).

A3.9 Drying, grinding, sieving, and homogenizing soil samples (Section adapted from FAO, 2019a)

If SOC and bulk density determinations are performed in the same sample, then field-moist samples of known volume should be weighed first, and then spreading it out as a thin layer in a shallow tray and air-dried in a ventilated room, a custom-made solar dryer, or a forced-air oven at 40°C. Large clods should be broken up to accelerate the drying process, avoid soil aggregation and to separate roots from fine soil to avoid contamination at sieving. Samples should then be crumbled and the fraction that passes through a 2 mm sieve separated for dry weight and SOC analysis. At sieving the > 2 mm

size rocks and pebbles (coarse fraction or gravel) should be separated and weighed for correcting the bulk density (see Annex A4 for SOC stocks estimations using bulk density). The fine earth fraction shall be thoroughly homogenized, which is best achieved by milling the sample. For further specifications on the laboratory methods, refer to Annex 5 based on GLOSOLAN Guides.

A3.10 Sampling materials and equipment

The following sampling materials are recommended for the field work (Nerger, 2019):

- Rust-free steel soil corer of 100 cm sample tube length or rust-free steel soil auger.
- Big non-rebound mallet to introduce auger.
- For bulk density measurements: 2 steel ring samplers with a known inside volume (preferably 100 cm^3), 1 fitting steel or wooden helmet to hammer the samplers in the soil and protection caps to protect the open side of the ring sampler when it is turned around to smooth the other open side.
- Transparent stable 3-litre plastic bags with zip-lock and zip-fastening system for soil samples.
- Large labeled plastic buckets to store the sampled soil when going around at the field and homogeneize soil to form composite samples.
- Waterproof markers for labeling the sample bags.
- Spade or shovel for stone content estimation and extraction of BD sample cylinders/rings from the soil.
- Field knife to remove soil material from the BD rings.
- Hand scraper, to clean BD rings when sampling.
- Garden trowel to remove soil material from the corer into the buckets.
- Brush, to roughly clean the corer and the equipment.
- Field towel to remove moist sample rests from the soil corer and the ring samplers.
- Either a ruler, a folding rule or a metal scale with a length and scale of at least 30 cm, to measure the soil layer depths.
- Set of working gloves, for hammering.
- Set of plastic gloves, for bulking the soil corer material in the buckets before filling them into the sampling bags.
- Waterproof clipboard with the paper soil sampling forms.
- Waterproof pens to fill out the soil sampling forms.
- GPS measurement device.
- Big stable bag to store the equipment efficiently while walking between the sampling points.
- Personal equipment: drinking water and food, robust shoes, mosquito repellent, sun shelter.


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Pexels

Annex 4 Soil organic carbon stock calculation sub-protocol

A4.1 Soil organic carbon stock equations (Section adapted from IPCC, 2006)

In this MRV, SOC stocks should be estimated using the bulk density of the fine earth (BDfine1), as in IPCC (2003, p. 90), (Equation A4.1):

$$SOCi\ stock\ (Mg\ C/ha) = OCi \times BDfineli \times (1 - vGi) \times ti \times 0.1$$

Equation A4.1

where,

SOCi (Mg C/ha) is the soil organic carbon stock of depth increment i

OCi (mg C/g fine earth) is the organic carbon content of the fine earth fraction (< 2 mm) in the depth increment i

BDfine1i (g fine earth/cm³ fine earth) is the mass of fine earth per volume of fine earth = (dry soil mass [g] – coarse fragment mass [g]) / (soil sample volume [cm³] – coarse fragment volume [cm³]) in the depth increment i

volume fraction fine earth (cm³ fine earth/cm³ soil) = 1 – volume fraction coarse fragment [cm³ coarse fragment/cm³ soil]

t is the thickness (depth, in cm) of the depth increment i

0.1 is a factor for converting mg C/ cm² to Mg C/ha

Alternatively, SOC stocks can be estimated from the fine soil stock of the investigated soil layer (FSS , t ha^{-1}), considering the mass of the fine soil fraction and the total volume of the sample, as in Poeplau, Vos and Don (2017), (Equation A4.2):

$$FSS = \frac{mass_{finesoil}}{volume_{sample}} \times thickness$$

Equation. A4.2

SOC Stocks can be estimated from fine soil stocks (FSS) and SOC concentration of the fine soil ($SOC_{con\ fine\ soil}$) as:

$$SOCstock = SOCcon_{finesoil} \times FSS$$

Equation A4.3

This has implications for sample preparation: for BDfine soil the volume of coarse fragments has to be estimated by weighing rock fragments and coarse roots separately, while FSSi would only need the total mass of the fine soil contained in the known volume of sample.

It is recommended to use the well-known IPCC formula described in Equation A4.1. However, Equation A4.6 is a simpler calculation for which fewer measurements are needed and less uncertainty is involved, as there is no need to determine or assume the volume of the coarse fraction. A disadvantage is that the user may still want to know the 'regular' bulk density as a diagnostic soil property. In this case, weighing the soil before and after sieving away the stones, BD, BDfine1 and BDfine2 can be calculated. If bulk density measurement is not possible, dry soil mass per volume to be weighed during soil sampling for the determination of SOC can be used in place of bulk density in the above equation to estimate SOC density/stock.

A4.2 Equivalent soil mass

Carbon stocks must be expressed in units of equivalent mass, to avoid the influence of different compaction states that involve soils of different weight. For this, the calculated stocks must be referred to an equivalent soil mass (Wendt and Hauser, 2013), which should exclude carbon concentration during the calculation of soil mass (dry). Assuming that in this case it is important to know whether or not there was additionality in the impact of the practices, it is taken as a criterion to express it on the basis of the less compact soil (i.e. lower bulk density).

In the example of Figure A4.1, the soil in the baseline situation has higher bulk density than that in the intervention situation.

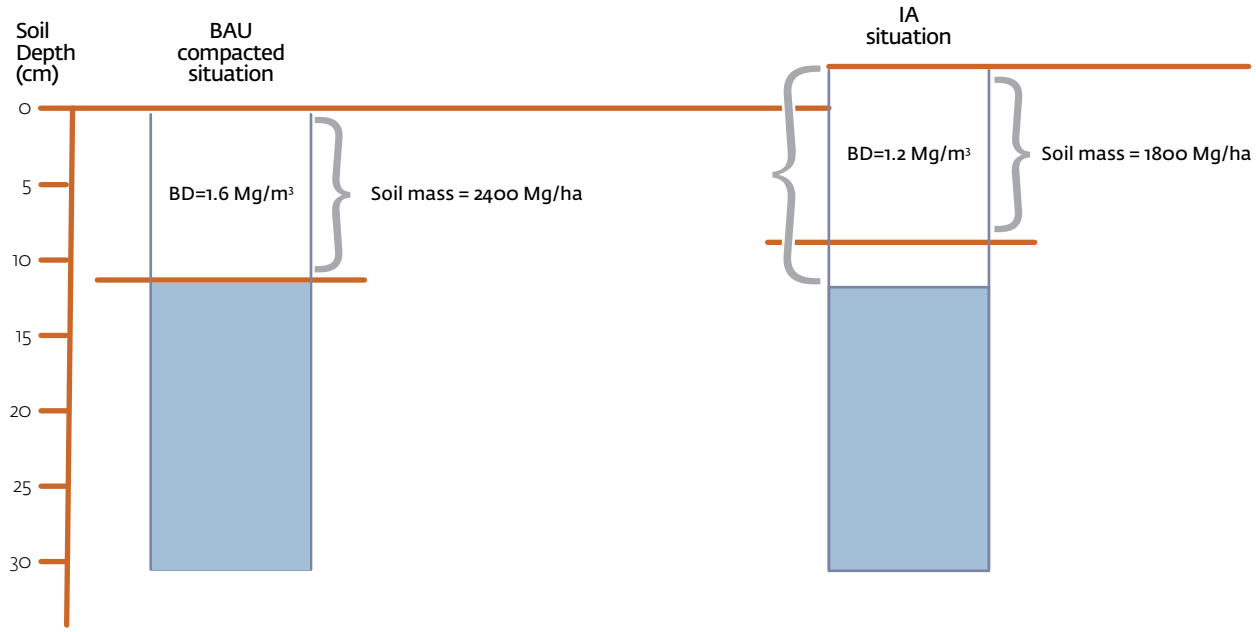


Figure A4.1 | Example of soils with different bulk densities to be compared in their SOC stocks (inspired by Wend and Hauser, 2013).

In this theoretical example, when expressed at equivalent volume, the soil after the intervention (IS) has a slightly higher SOC stock (+2.4 t C ha^{-1}) than that at the baseline condition (year 0). However, when expressed at equivalent soil mass (4,400 t ha^{-1} as reference) this plus of SOC stock reaches 5.183 t C ha^{-1}. This is so because of the different bulk densities and soil masses in the top 30 cm of soils at the baseline and IS conditions.

Table A4.1 | shows a theoretical example of calculation of SOC stock expressed at equivalent soil mass of Figure A4.1. The lighter soil was taken as a reference; in this case the soil in the IS situation.

a) Soil mass estimation

Soil at BAU condition

		A	B	C	D=A x B x C	E= D1 + D2
	Soil layer	**1 ha**	**BD**	**thickness**	**Soil mass layer**	**Soil mass 0-30 cm**
		m^2	**t . m^{-3}**	**m**	**$t.ha^{-1}$**	**$t.ha^{-1}$**
1	0-10 cm	10000	1,4	0,1	1400	
2	10-30 cm	10000	1,6	0,2	3200	4600

Soil at IA condition

		A	B	C	D=A x B x C	E = D3+D4
	Soil layer	**1 ha**	**BD**	**thickness**	**Soil mass layer**	**Soil mass 0-30 cm**
		m^2	**t . m^{-3}**	**m**	**$t.ha^{-1}$**	**$t.ha^{-1}$**
3	0-10 cm	10000	1,2	0,1	1200	
4	10-30 cm	10000	1,6	0,2	3200	4400

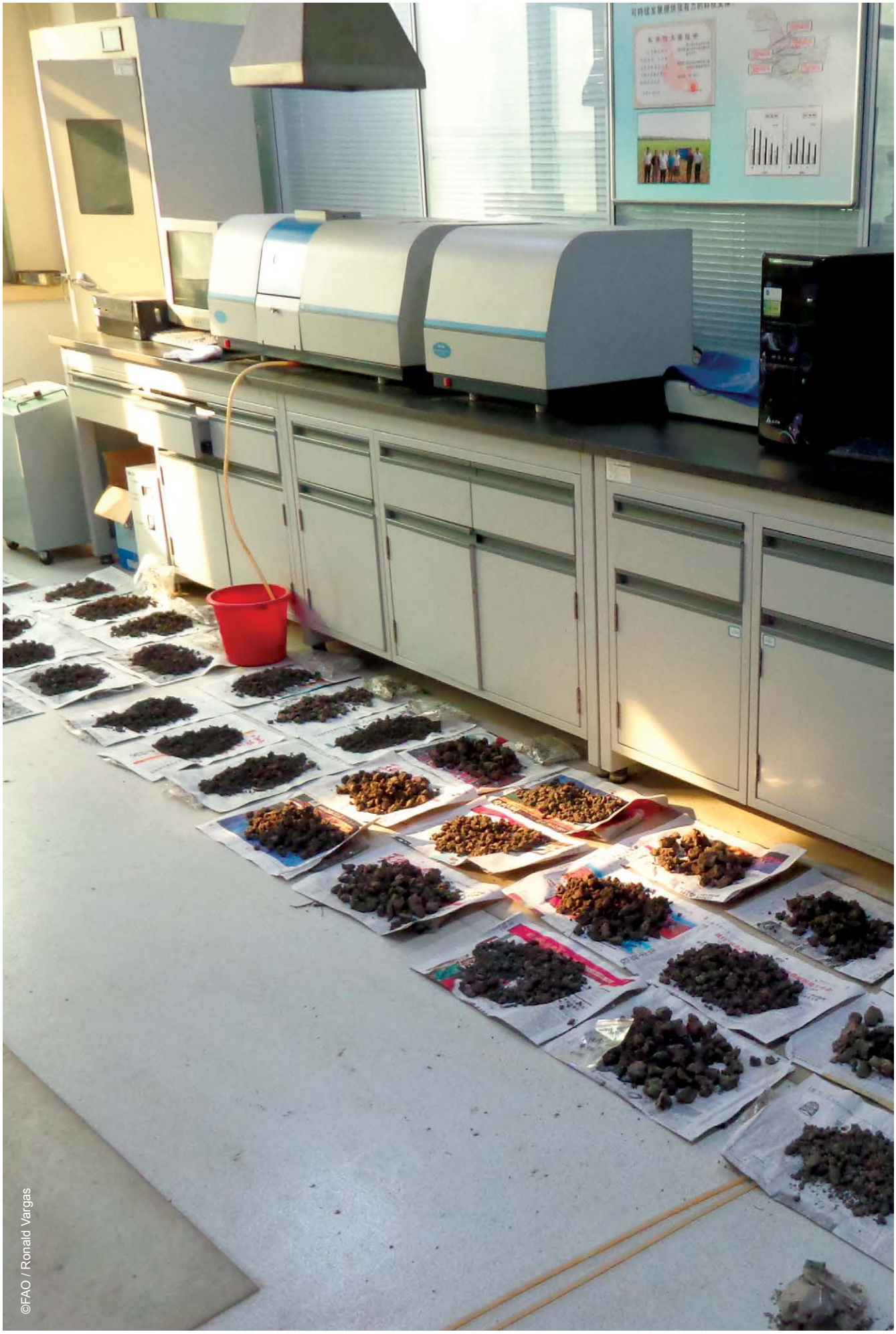
b) SOC stock estimation

Soil at BAU condition

		F	G = (D x F)/100	H = G1+G2	I = H2 x E4/E2	J= I4-I2
	Soil layer	**SOC**	**SOC stock**	**SOC stock 0-30 cm**	**SOC stock equivalent soil mass**	**Additional SOC stock**
		%	**t . m^{-3}**	**t.ha^{-1}**	**t.ha^{-1}**	**t.ha^{-1}**
1	0-10 cm	1,6	22,4			
2	10-30 cm	1,3	41,6	64	**61,22**	**5,18**

Soil at IA condition

		F	G = (D x F)/100	H = G3+G4	I =H3 x E4/E4	J= J4-J2
	Soil layer	**SOC**	**SOC stock**	**SOC stock 0-30 cm**	**SOC stock equivalent soil mass**	**Additional SOC stock**
		%	**t . m^{-3}**	**t.ha^{-1}**	**t.ha^{-1}**	**t.ha^{-1}**
3	0-10 cm	1,8	21,6			
4	10-30 cm	1,4	44,8	66,4	**66,40**	-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Annex 5 Laboratory methods sub-protocol

Soil samples arriving at the lab will be analyzed to determine their concentration of soil organic carbon and particulate organic carbon, according to the monitoring stage of the protocol.

- There is no single method for determining organic carbon in soil samples, but this protocol applies for two widely used and accepted methodologies: wet oxidation (Walkley and Black, 1934), following GLOSOLAN protocols (FAO, 2019c), and Dumas dry combustion method (described in Section A5.2, following GLOSOLAN standard operating procedures, FAO, 2019c). The dry combustion method shall be the preferred option when possible.
- Particulate organic carbon (described in Section A5.3, following Cambardella and Elliot, 1993).

The same procedures must be conducted along the monitoring stage, and preferably, the same laboratory should be used for the determinations. In GLOSOLAN there are National Reference Laboratories that use harmonized methods and protocols for lab analysis.

A5.1 Standard operating procedure for soil organic carbon (SOC): Walkley-Black method, titration and colorimetric method. Extracted from GLOSOLAN Standard Operating Procedures (FAO, 2019c).

Global Soil Laboratory Network GLOSOLAN	GLOSOLAN-SOP-02	
SOIL ORGANIC CARBON WALKLEY-BLACK METHOD: Titration and Colorimetric Method	Version number : 1	Page 1 of 25
	Effective date : October 28, 2019	

A5.1.1 Scope and field of application

This sub-protocol applies to the determination of the Oxidizable Organic Carbon content in soil. Organic carbon content is calculated from the amount of chromic ion (Cr^{3+}) formed, using a titration or colorimetric method, the presence of chloride (>0.5% Cl^-) will produce a positive interference in saline soils. The bias resulting from the presence of chloride can be corrected if required (Rayment and Lyons, 2011). This method is described in Nelson and Sommers (1983) and the test method described here does not routinely apply correction for chloride.

A5.1.2 Principle

The determination of soil organic carbon is based on the Walkley and Black chromic acid wet oxidation method. Oxidizable organic carbon in the soil is oxidized by 0.167 M potassium dichromate ($K_2Cr_2O_7$) solution in concentrated sulphuric acid. The heat of reaction raises the temperature which is sufficient to induce substantial oxidation.

Chemical reaction is as follows:

$$2\,Cr_2O_7^{2-} + 3\,Co + 16\,H^+ \; 4\,Cr^{3+} + 3\,CO_2 + 8\,H_2O$$

The $Cr_2O_7^{2-}$ reduced during the reaction with soil is proportional to the oxidisable organic C present in the sample. The organic carbon concentration can then be estimated by measuring the remaining unreduced dichromate by back-titrating with ferrous sulphate or ammonium ferrous sulphate using diphenylamine or o-phenanthroline-ferrous complex as an indicator.

$$6\,Fe^{2+} + Cr_2O_7^{2-} + 14\,H^+ \; 2\,Cr^{3+} + 6\,Fe^{3+} + 7\,H_2O$$

Alternately the organic carbon can be calculated from the amount of chromic ion (Cr^{3+}) formed, using a colorimetric procedure measuring absorbance at 588 nm (after Sims and Haby, 1971). An advantage of this procedure over the titrimetric method is that accurate standardization of the $Cr_2O_7^{2-}$ solution is not required.

Points to be noted:

1. Recoveries of the total Soil Organic Carbon by this method can typically be between 75 – 90 % in surface soils and will vary with soil type and depth. Walkley and Black found that on the average about 77% of the organic C was recovered by the heat of dilution procedure, and they proposed that a correction factor of 1.3 be used to account for unrecovered organic C;

2. This method is subject to interferences by certain soil constituents that lead to false results with some soils. Chloride, ferrous iron and higher oxides of Mn have been shown to undergo oxidation-reduction reactions in chromic acid mixtures leading to incorrect values for organic C. The presence of significant amounts of Fe^{2+} or Cl^- in soil will lead to a positive error, whereas reactive MnO_2 in soil samples will result in a negative error and low values for organic C. The addition of H_3PO_4 after the sample has cooled helps eliminate interferences from the ferric (Fe^{3+}) ion that may be present in the sample. Chloride interference can be eliminated by washing the soil free of Cl^- before analysis or precipitating the Cl^- as AgCl by addition of Ag_2SO_4 to the digestion acid;

3. For soils that are very high in organic carbon content, the Walkley and Black method may result in low test results, due to the incomplete oxidation of the organic carbon in the sample. Smaller sample weights should be used for samples with very high carbon content;

4. This method is for the determination of organic carbon in soils. It is not applicable to soils containing significant amounts of carbonized materials.

A5.1.3 Apparatus

A5.1.3.1 For titration method

Analytical balance, with an appreciation of 0.0001 g for the preparation of reagents

- Precision balance, with an appreciation dependent on the weight of the sample (Table 1).
- Burette 50 mL, with an appreciation of ± 0.02 mL for the titrant solution.
- Volumetric burette/ dispenser of 10.00 mL ± 0.01 mL, of known uncertainty, to be used with the potassium dichromate solution.
- Volumetric dispenser, adjusted to 20.0 mL, to be used with concentrated sulphuric acid.
- Erlenmeyer flasks, 500 mL
- Magnetic stirrer and bar.
- Oven able to reach a temperature of 105ºC.
- Volumetric flasks; 1000 mL
- Glass rod.
- Beaker; 100 mL, 250 mL
- Fumehood – extraction/ventilation.
- Burette and stand.

A5.1.3.2 For colorimetric method

- Analytical balance, with an appreciation of 0.0001 g for the preparation of reagents.
- Spectrophotometer suitable for measuring absorbance at 600 nm wavelength.
- Centrifuge tubes (can withstand ≥ 130°C of heat) or glass conical tubes, about 50-75 mL capacity.
- Dispensing or volumetric pipettes, 1mL, 5 mL 4.2.5. Graduated pipettes; 1mL, 2 mL
- Calibrated dispenser; 2 mL, 5 mL, 10 mL.
- Glass rod 4.2.8. Volumetric flasks; 100 mL, 500 mL.
- Beaker; 100 mL, 250 mL.

A5.1.4 Materials

A5.1.4.1 For titration method

- Deionized water/distilled water, it should have an EC < 1.5*10-3 dS m-1
- Potassium Dichromate Standard, 0.167 M (1.0 N) Dissolve 49.04 g of traceable or equivalent analytical grade $K_2Cr_2O_7$ (previously dried at 105°C for 2 hours and cooled in a desiccator to room temperature) in deionized/distilled water, and dilute the solution to a volume of 1000 mL.
- Sulphuric Acid, Concentrated (not less than 96%) - For Titration and Colorimetric Method If Cl- is present in soil, add Ag_2SO_4 to the acid at the rate of 15 g per litre.
- Phosphoric Acid, 85% (If Diphenylamine indicator is used) The phosphoric acid is

added to form a complex with the interfering iron (III), providing a sharper color change of the indicator.

- Indicator (either 5.1.5.1 or 5.1.5.2 can be chosen).
- o-Phenanthroline - Ferrous Complex, 0.025 M Dissolve 1.485 g of o-phenanthroline monohydrate (analytical grade) and 0.695 g of ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$) (analytical grade) in deionized/distilled water. Dilute the solution to a volume of 100 mL. The o-phenanthroline-ferrous complex is also available under the name of Ferroin from the G. Frederick Smith Chemical Co. (Columbus, Ohio).
- Barium diphenylamine sulfonate Indicator, 0.16% aqueous solution.
- Titrant (either 5.1.6.1 or 5.1.6.2 can be chosen).
- Ferrous Sulphate (FeSO4) solution, 0.5 M Dissolve 140 g of analytical grade $FeSO_4 \cdot 7H_2O$ in deionized/distilled water, add 15 mL of concentrated sulphuric acid, cool the solution, and dilute it to a volume of 1000 mL with deionized/distilled water. Standardize this reagent daily by titrating it against 10 mL of 0.167 M (1 N) potassium.
- Ferrous Ammonium Sulphate, 0.5 M Dissolve 196 g of analytical grade (NH4)2 $Fe(SO_4)_2.6H_2O$ in 700 mL of distilled water, add 20 mL of concentrated sulphuric acid, cool the solution, and dilute it to a volume of 1000 mL with distilled water. Standardize this reagent daily by titrating it against 10 mL of 0.167 M potassium dichromate.

Note: The Fe^{2+} in both solutions oxidizes slowly on exposure to air so it must be standardized against the dichromate daily. Prepare a new solution every 30 days.

A5.1.4.2 For colorimetric method

- Deionized water/distilled water, it should have an EC < 1.5*10-3 dS m-1
- Potassium Dichromate, 10% (0.34 M) Dissolve 50.0 g of traceable or equivalent analytical grade $K_2Cr_2O_7$ in 500 mL deionized/distilled water.
- Sucrose Standard, 4 mg C/mL Weigh 0.95 g sucrose (dried at 1050C for two hours) and dissolve in 100 mL deionized/distilled wáter. 6. Health and safety

This procedure involves the use of hazardous chemicals. Refer to laboratory safety guidelines or Material Safety Data Sheet (MSDS) before proceeding.

A5.1.5 Personnel safety

Safety glasses, gloves and lab coats must be worn when handling any chemicals.

Chemical hazard

- Potassium dichromate is an inorganic compound that emits toxic chromium fumes upon heating. Potassium dichromate is highly corrosive and is a strong oxidizing agent. This substance is a known human carcinogen and is associated with an increased risk of developing lung cancer.
- Sulphuric acid: Keep away from naked flames/heat. Measure the concentration in the air regularly. Carry out operations in a fume hood with exhaust/ventilation. Do not discharge the waste into the drain. Never dilute by pouring water into the acid. Always add the acid to the water.
- Hygiene: Wash hands and clean other exposed areas with mild soap and water after using all chemical reagents

All titrations and handling of chemicals to be undertaken in a fume hood.

A5.1.6 Sample preparation

Air dry soil sample and sieve to ≤ 2.0 mm size.

A5.1.7 Procedure

A5.1.7.1 Titration method

Steps:

1) Weigh 1.0 g of air dried soil (adjust if necessary, see guideline recommended from Table 1) into a 500 mL erlenmeyer flask.

2) Add 10 mL of 0.167 M $K_2Cr_2O_7$ and swirl the flask gently to disperse the soil in the solution.

3) Then with care, rapidly add 20 mL concentrated H_2SO_4, directing the stream into the suspension.

4) Immediately swirl the flask gently until soil and reagents are mixed, then more vigorously for a total of 1 min.

5) To minimize heat loss, allow the flask to stand on an insulated sheet for 30 min in a fume hood.

6) Add 200 mL of water to the flask.

Remark: Filter the suspension using an acid resistant filter paper (e.g. Whatman No. 540), if experience shows that the end point of the titration cannot otherwise be clearly discerned.

7) Add 10 mL of 85% H_3PO_4.(if barium diphenylamine sulfonate indicator is used).

8) Add three to four drops of o-phenanthroline indicator or barium diphenylamine sulfonate indicator and titrate the solution with 0.5 M $FeSO_4$ solution or 0.5 M $(NH_4)_2 Fe(SO_4)_2.6H_2O$.

9) As the end point is approached:

   9.1) "Ferroin" Titration, when using the o-phenanthroline indicator, the solution takes on a greenish cast and then changes to a dark green. At this point, add the ferrous sulfate heptahydrate drop by drop until the color changes sharply from blue to red (maroon color in reflected light against a white background).

   9.2) "Diphenylamine" Titration, when using the diphenylamine indicator, near the end-point the color changes to deep violet-blue; slow down the titration by adding the ammonium ferrous sulphate dropwise. At the endpoint the color changes sharply to brilliant green.

   Determine 1-3 blanks in the same manner, but without soil, to standardize the $K_2Cr_2O_7$.

10) Compute for the %OC with the computation given at Section 9.1 and report as oven-dry basis with two (2) decimal places.

Table A5.1 | Recommended weight of sample for analysis

Weight, g	OC, %	Color
0.1	>2	black, dark gray, dark brown
0.25	≤2	brown - dark brown, gray - dark gray
0.5	<0.6	Brown

Note: Above is just a guide for determining the appropriate weight to be used for each sample based on soil color. % OC may vary per soil color type. Generally, dark colored soils that are described as dark brown to black show a higher content of carbon and nitrogen than soils that are lighter in color. The table is just a guide and is not applicable for example in oxisols in tropical and subtropical regions.

Manual potentiometric titration

1. Set an expanded scale pH/mV meter with a platinum electrode and calomel reference electrode to read E (mV). Insert the electrodes and temperature compensator in the solution and stir with a magnetic stirrer. Tall form beakers can be used as an alternative to Erlenmeyer flasks giving more room for the electrodes, temperature compensator and burette.

2. Using one of the unknowns, plot a titration curve by recording values of measured E (mV) and mL titrant (0.5 M $FeSO_4$ or 0.5 M $(NH_4)_2 Fe(SO_4)_2.6H_2O$ added from a burette. The end point is then found on the point of inflexion on the curve (approximately 750 mV). Subsequent titrations are discontinued when this point is reached, and the corresponding titrant consumption is then measured. If over 8 mL of the 10 mL of the dichromate has been reduced, the determination must be repeated with a smaller amount of soil sample.

Automatic potentiometric titration

Use an auto titrator with a platinum electrode to the mV terminal and calomel reference electrode to the glass electrode terminal.

Use a 25 mL autoburette for the 0.5 M FeSO4 or 0.5 M $(NH_4)_2$ $Fe(SO_4)_2.6H_2O$ titrant.

The titration is carried out by first plotting a titration curve as described above and then automatically titrating to the end-point (approximately 750 mV) thus determined. Titrator settings should follow the Titrator Equipment Handbook.

If over 8 mL of the 10 mL of the dichromate has been reduced, the determination must be repeated with a smaller amount of soil sample.

A5.1.7.2 Colorimetric method

Steps:

1) Preparation of Standards curve

2) Prepare a set of sucrose standards (0-8 mg C) as specified in the table below in centrifuge tubes. Volumes of sucrose standard and deionized/distilled water corresponding to the mass of organic carbon.

3) To each tube, add 2.0 mL 10% $K_2Cr_2O_7$ (0.34 M) solution and mix.

4) Add 5.0 mL H_2SO_4, cool and stand for 30.0 minutes.

5) Add 18.0 mL deionized/distilled water to the tube.

Table A5.2 | Standard Preparation

Mass of OC. (mg)	Sucrose Standard (4 mg C/mL) (mL)	H_20 (mL)
0	0.00	2.00
1	0.25	1.75
2	0.50	1.50
3	0.75	1.25
4	1.00	1.00
5	1.25	0.75
6	1.50	0.50
7	1.75	0.25
8	2.00	0.00

6) Preparation of Samples

6.1.) Weigh 0.5 g soil sample (refer to Table 1 if sample mass is to be modified)

6.2.). Add 2.0 mL 10% (0.34 M) $K_2Cr_2O_7$ solution and mix

6.3.) Add 5.0 mL H_2SO_4, cool and stand for 30.0 minutes.

6.4.) Add 20.0 mL water to the tube. Mix and stand overnight.

7) Measurement

Read the absorbance of the calibration standards and samples in a spectrophotometer set at 600 nm wavelength.

When the correlation coefficient of the calibration curve is equal to, or greater than, 0.9990, proceed with the analysis of samples. Otherwise, verify that the standards and reagents were correctly prepared, the instrument is functioning properly, and that the instrument set-up is correct. Corrective actions must be taken and details of corrective action recorded.

8) Reporting

Compute for the %OC with the computation, and report as oven-dry basis with two (2) decimal places.

A5.1.8 Calculations

A5.1.8.1 Titration method

From the equation:

$2\ Cr_2O_7^{2-} + 3\ Co + 16\ H^+ \rightarrow 4\ Cr^{3+} + 3\ CO_2 + 8\ H_2O$

1 mL of 1 N dichromate solution is equivalent to 3 mg of carbon

After the reaction, the excess Cr_2O_7 is titrated with 0.5 M $FeSO_4$ or 0.5 M $(NH_4)_2$ $Fe(SO_4)_2.6H_2O$

$$6\ Fe^{2+} + Cr_2O_7^{2-} + 14\ H^+ \leftrightarrow 2\ Cr^{3+} + 6\ Fe^{3+} + 7\ H_2O$$

$$Organic\ C, \% = \frac{(V_{blank} - V_{sample}) \times M_{Fe^{2+}} \times 0.003 \times 100 \times f * mcf}{W}$$

where:

V_{blank} = volume of titrant in blank, mL

V_{sample} = volume of titrant in sample, mL

$M_{Fe^{2+}}$ = concentration of standardized $FeSO_4$ or $(NH_4)_2$ $Fe(SO_4)_2.6H_2O$ solution, molarity

0.003 = carbon oxidised (shown below)

$$= \frac{12\ g\ C}{mole} \times \frac{1\ mole\ K_2Cr_2O_7}{6\ moles\ FeSO_4} \times \frac{3\ moles\ C}{2\ moles\ K_2Cr_2O_7} \times \frac{1\ L}{1000\ mL}$$

f = correction factor, 1.3

W = weight of soil, g

mcf = Moisture correction factor *(refer to SOP for Moisture Content to compute for the mcf value)*

Note: An oxidation correction factor of 1.3 is required because, on average, only about 77% of organic carbon is recovered by this method. However, it should be considered that the value of this factor is very variable, since it is conditioned by the type of soil and by the nature of the organic matter.

A5.1.8.2 Colorimetric method

$$\%\ OC = \frac{mgC_{sample} - mgC_{blank}}{w,mg} \times f \times mcf \times 100$$

where:

% OC = Organic Carbon content of the soil, %

mg C_{sampl} = Analyte/concentration of C in sample

mg C_{blank} = Analyte/concentration of C in blank

W = Mass of air dry sample, mg

f = Correction factor, 1.3

mcf = Moisture correction factor *(refer to SOP for Moisture Content to compute for the mcf value)*

A5.1.9 Quality assurance/quality control

Accuracy test

- Participate in an Inter-laboratory Proficiency Test at least once a year. The PT z-score should be less than 2. If not, identify root cause, develop corrective and preventive actions, and address the problem.
- Perform replicate analyses of the Certified Reference Material (CRM). Compare results of selected laboratory with results of other laboratories as provided in the performance analysis report, or CRM certificate. The own laboratory result is considered accurate when it falls within the reported 95% confidence interval of the target value.

Precision test

- Perform replicate analysis of 10% of samples in a test batch. Calculate the Percent Relative Standard Deviation (%RSD) to determine the precision of replicate analyses is within specification. Compare the result with the target precision for the analyte concentration (Table A5.3).

$$\%\ RSD = \frac{s}{\bar{x}} \times 100$$

Where: s = standard deviation of the replicate result
x̄ = mean

Analyte, %	Analyte ratio	Unit	RSD, %
100	1	100%	1.3
10	10^{-1}	10%	1.9
1	10^{-2}	1%	2.7
0.01	10^{-3}	0.1%	3.7
0.001	10^{-4}	100 ppm (mg/kg)	5.3
0.0001	10^{-5}	10 ppm (mg/kg)	7.3
0.00001	10^{-6}	1 ppm (mg/kg)	11
0.000001	10^{-7}	100 ppb (µg/kg)	15
0.0000001	10^{-8}	10 ppb (µg/kg)	21
0.00000001	10^{-9}	1 ppb (µg/kg)	30

Control chart

Analyze at least a duplicate of the Check Sample or Internal Reference Material for every batch of analysis. Plot the result in the control chart. Monitor out-of-specified limits. If out-of-specified limit is observed, identify the root cause and develop corrective and preventive actions.

A5.2 Standard operating procedure for soil total carbon: Dumas dry combustion method. Extracted from GLOSOLAN Standard Operating Procedures (FAO, 2019c).

Global Soil Laboratory Network GLOSOLAN	GLOSOLAN-SOP-03	
SOIL TOTAL CARBON Dumas dry combustion method	Version number : 1	Page 1 of 10
	Effective date : October 28, 2019	

A5.2.1 Scope and field of application

The Dumas dry combustion method determines total carbon, representing all chemical forms of C in the soil. Other methods may be used to quantify the various forms of carbon. For example, the Walkley and Black method measures oxidizable organic carbon. For analysis of TC by dry combustion, an automatic chemical analyser, commonly known as an autoanalyzer, is used. Advantages of using an autoanalyzer are increased accuracy and

versatility. An autoanalyzer can be used to quantify carbon, nitrogen, and sulphur. Disadvantages of using an autoanalyzer are equipment initial cost, operating and maintenance costs, and the lower number of labs using an autoanalyzer worldwide. Additional care must be taken during sample preparation if quantifying TC by the Dumas dry combustion method. A very small sample is used, which requires the samples to be well homogenized.

The procedure measures both organic C and inorganic C together. To quantify the organic C fraction only, the inorganic C fraction must be removed or quantified prior to autoanalyzer analysis. Alternatively, the inorganic C can be quantified separately and then subtracted from the TC.

A5.2.2 Principle

This method is based on the Dumas dry combustion principle. The sample is burned at high temperature (between 900 and 1000 °C or 1400 and 1600 °C) in an atmosphere of pure oxygen. Under these conditions, all C-containing compounds are completely decomposed and converted into carbon oxides (mainly carbon dioxide). The autoanalyzer measures and reports the TC value based on the concentration of carbon oxides present using various procedures (for example, a C gas detector and thermal differences between gas columns).

A5.2.3 Apparatus

- Autoanalyzer for C, with all specific accessories and consumables, including appropriate detection system. The equipment might also analyse N and S, depending on the manufacturer and model.
- Analytical balance, ±0.0001 g, to weigh samples and reference materials.
- Milling system that meets the requirements of the autoanalyzer manufacturer.
- Crucible set (if needed), depending on the sample size used by the autoanalyzer.

A5.2.4 Materials

- Certified Reference Material (CRM) with known C content to calibrate the autoanalyzer. The CRM may vary depending on the autoanalyzer manufacturer. Aspartic acid, EDTA, acetanilide, or soil samples with certified total C content may be used.
- Oxygen gas (O_2), along with reference or carrier gases (He, for example), of very high purity (greater than 99.99%).
- Consumables specific to the autoanalyzer.

A5.2.5 Health and safety

This procedure does not imply the direct use of dangerous chemical reagents, but appropriate safety precautions are necessary. Catalyser residues are toxic and must be disposed of properly. Gloves, lab coats, and eye protection must be worn when handling reagents and samples. When a special reagent is used (for example, a reference material for equipment control), consult the material safety data sheet (MSDS) and conduct a risk assessment. Take necessary precautions when handling compressed gasses and high-temperature equipment. Follow the manufacturer's safety guidelines when operating the autoanalyzer.

A5.2.6 Sample preparation

Follow the sample preparation instructions provided by the manufacturer for use of the autoanalyzer. Probably, a representative portion of the soil sample that was previously treated (dried and sieved to 2 mm) must be porfirised (grind fine and homogeneously) until the entire fraction passes through a sieve of inferior size. Typically, a representative subsample is taken from the bulk sample and milled to a sufficiently fine mesh size. Ensure that milling equipment and sieves do not introduce contamination to the samples.

A5.2.7 Procedure

A5.2.7.1 Calibration of the apparatus.

Calibrate the equipment as described in the autoanalyzer instruction manual. Use a CRM provided or recommended by the manufacturer (soil, acetanilide, calcium carbonate, EDTA, glucose anhydrous, etc). The CRM should cover the range of TC typically found in test samples. Store all CRM as indicated by the manufacturer label. Replicated blanks must also be analysed to determine the baseline according to the specific equipment procedure.

A5.2.7.2 Determination of the total carbon (TC) content

Because the analysis procedure varies between manufacturer's, analyse samples according to the manufacturer's guidelines for soil analysis. The mass of the sample weighed is dependent on the TC of the sample and the linear range of the autoanalyzer. To check autoanalyzer performance, CRM, control samples, and blanks should be incorporated at regular intervals in each test batch. The number and frequency of control and check samples depends on the method used and the calibration stability of the autoanalyzer.

A5.2.8 Calculation

Report TC using the International Units System as: grams of C (g) per kilogram (kg) of soil, g/kg. Results must be reported on an oven dry soil basis.

The number of decimals reported must conform to the conventional rules of maintaining 3 numbers:

- values greater than 100, no decimal reported;
- values between 10 and 100, 1 decimal (0.1) reported; and
- values less than 10, 2 decimals (0.01) reported.

A5.2.9 Quality assurance/quality control

Precision test

- 5 percent of the samples in a test batch must be replicates to guarantee at least one duplicate sample if the batch is small.
- Calculate the percent relative standard deviation (% RSD) to determine precision.

$$\% \ RSD = \frac{S}{\bar{x}} \times 100$$

s = standard deviation of the replicate result
$\bar{x}$ = mean

- Compare the result with the previously specified precision.

The acceptance requirements for precision testing must be defined by the equipment used, environmental conditions, and other testing factors and by the specifications or requirements for the information use and agronomic criteria. If the precision test fails, the cause of the failure must be identified and corrective or preventive actions must be developed.

Recovery test

- Perform triplicate analysis of Certified Reference Material of the analysed matrix (soil) (CRMs) or an Internal Reference Material (IRM), in accordance with the present SOP.

Note: To assess instrument performance, this procedure should be replicated with different levels of TC. Different levels can be selected by using CRM with different concentrations of TC or by simply weighing different masses of the same CRM.

- Calculate the percent recovery based on the equation below.
- Compare the result with the recovery target

$$\text{Recovery} = \frac{\text{mean of observed values}}{\text{true value}} \text{ x } 100$$

(%), which is predefined for the usual range of work.

The recovery target must be defined for the usual range of work. The definition should consider the working conditions (for example the characteristics of the equipment used and the environmental conditions). It should also consider the specifications or requirements for the given use of the information and for any agronomic criteria. The recovery can also be considered acceptable if it is within the 95% confidence interval reported for the target value of the CRMs.

If the recovery test fails, the cause of the failure must be identified and corrective or preventive actions must be developed.

Interlaboratory comparison

The laboratory must participate, at least once a year, in interlaboratory proficiency tests. If the obtained result is questionable or unsatisfactory, it is necessary to carry out an evaluation, identify the root cause of the problem, and develop corrective and preventive actions.

Control chart

- Perform the replicate analysis of a control sample or an IRM in a test batch of samples.
- Plot the result in a control chart.
- Monitor the results.

If results are out of specified limits (or tend to be so), an evaluation must be made. The cause of the noncompliance must be identified, and corrective and preventive actions must be developed.

A5.3 Standard operating procedure for particulate organic carbon. Adapted from Cambardella and Elliot (1993)

A5.3.1 Particulate organic carbon

Turnover of soil organic matter (SOM) is coupled to the cycling of nutrients in soil through the activity of soil microorganisms. Biological availability of organic substrate in soil is related to the chemical quality of the organic material and to its degree of physical protection. SOM fractions can provide information on the turnover of organic matter (OM), provided the fractions can be related to functional or structural components in soil.

Information on the turnover of soil organic matter can be obtained by using soil fractions, provided the isolated fractions can be related to structural or functional components in soil, and thereby, to biological turnover (Christensen, 1987). Physical fractionation of soil according to particle size has been used extensively to study soil organic matter (Edwards and Bemner, 1967; Turchenek and Oades, 1979; Anderson *et al.*, 1981; Tiessen and Stewart, 1983; Christensen, 1985; Balesdent *et al.*, 1988; Jocteur Monrozier *et al.*, 1991) and the methods have proven to be useful in revealing differences in the structural and dynamic properties of organic matter (OM) from different soils and particle size fractions (Christensen, 1987).

Particulate organic matter (POM) is the organic fraction between 2000 and 53 µm soil separates (Cambardella and Elliott, 1993) of which the carbon concentration is referred to as particulate organic carbon (POC). Research in carbon fractionation has indicated that POC is more sensitive to changes in management practices than total organic carbon (Chan, 2006; Bongiorno *et al.*, 2019).

Isolated by sieving or filtration, this fraction includes partially decomposed organic residues (Haynes, 2005) and contains microbial biomass together with fresh plant residues and decomposing organic matter (Gregorich *et al.*, 1994). POC is thus biologically and chemically active and is part of the labile (easily decomposable) pool of soil organic carbon (SOC).

A5.3.2 Laboratory methods

Steps according to Cambardella and Elliot (1993) and Chan (2001):

1) Break apart soil cores and pass them through a 2-mm sieve.
2) Dry the sieved soil overnight at 50 °C.
3) Store at 4 °C if necessary.

4) Disperse 10 grams of soil by shaking for 15 hours on an end-over-end shaker/ reciprocal shaker in 30 ml of 5 g l ±1 sodium hexametaphosphate solution.

5) Pass the dispersed solution through a 53 µm sieve.

6) Rinse several times with distilled water.

7) The soil slurry passing through the sieve contains the mineral-associated and water-soluble C.

8) Evaporate water in the slurry in a forced-air oven at 50 °C and ground the dried sample with a mortar.

9) Analyze for total soil organic carbon (see wet oxidation or dry combustion methods, Annex A5.1 and A5.2).

10) Determine C contents from a non-dispersed soil sample (see wet oxidation or dry combustion methods, Annex A5.1 and A5.2).

11) The difference between the C contents for the evaporated soil slurry and those obtained from a non-dispersed soil sample are considered to be equal to the C retained on the sieve, and equal to the Particulate Organic Carbon.

Annex 6 Spectroscopic techniques (from FAO, 2019a)

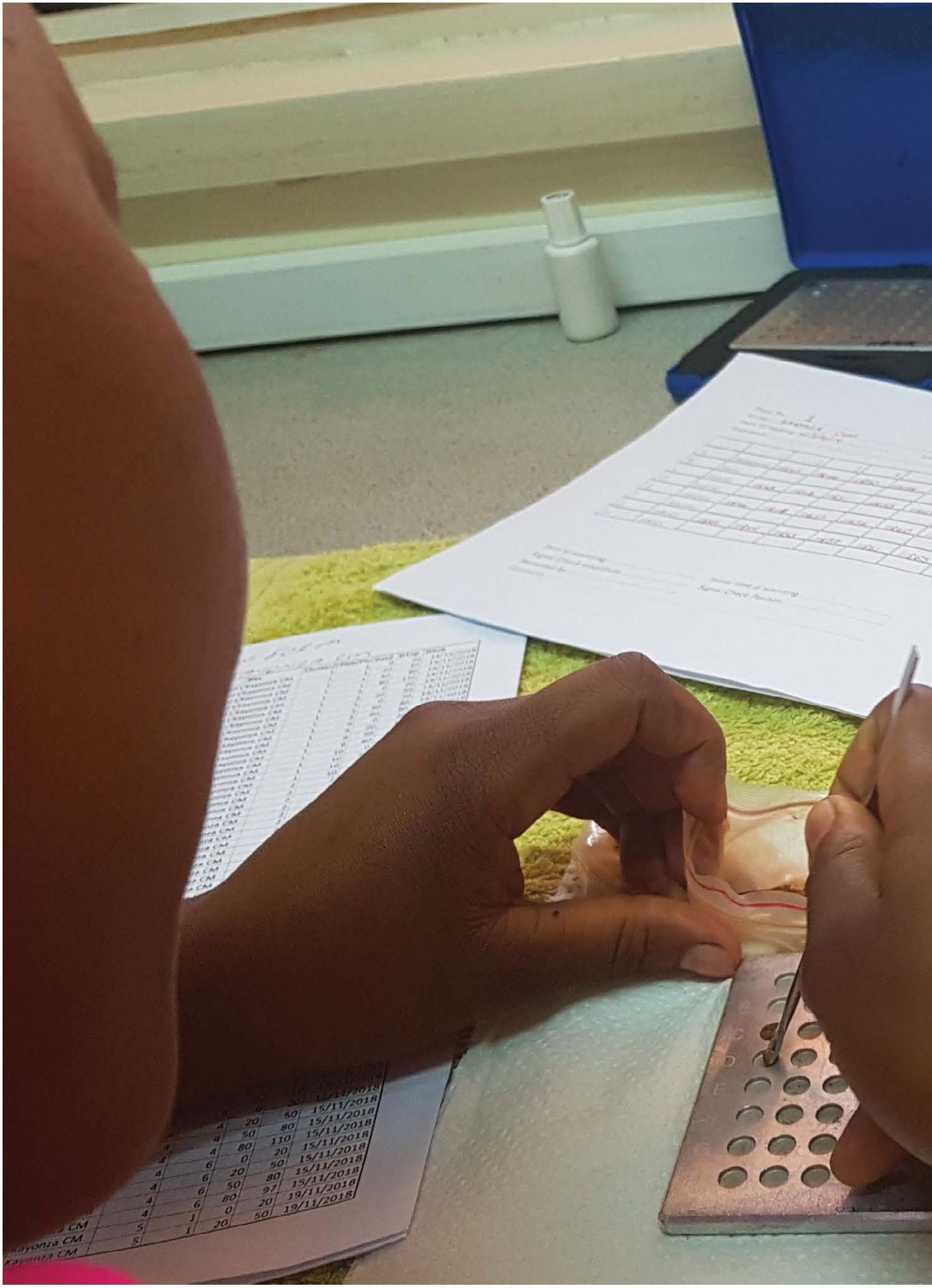
Soil organic carbon determination with the dry combustion and wet oxidation methods is often time and cost intensive and laborious, especially if large number of samples must be analysed (See Section A4, Sampling number). Having a large amount of SOC data could also help reduce measurement uncertainties due to high spatial variability in SOC content.

Spectroscopy offers a relatively rapid, low-cost, non-destructive alternative to conventional SOC testing (Bellon-Maurel and McBratney, 2011; Viscarra Rossel *et al.*, 2016). Soil spectroscopy uses the interaction of electromagnetic radiation with matter to characterize the physical and biochemical composition of soil sample. The principle is that light is shone on a soil sample and properties of the reflected light (visible-near-infrared, near infrared, or mid-infrared) are representatives of molecular vibrations that respond to the mineral and organic composition of soils. Reflected or absorbed light is collected at different wavelengths by a detector. The resulting pattern is referred to as a spectrum. Spectral signatures thus provide both an integrated signal of functional properties as well as the ability to predict several conventionally measured soil properties (Nocita *et al.*, 2015).

There are numerous mathematical methods and their combinations that have been tested for the development of models that estimate SOC and other soil properties (Gobrecht *et al.*, 2014). Chemometric models can be developed for different scales, from regional to local, of SOC determination (Madari *et al.*, 2005; Clairotte *et al.*, 2016). Depending on the scale, representativeness of the calibration sample set, spectral pre-treatment and the chemometric methods and sampling approach (Jiang *et al.*, 2017; Guo *et al.*, 2017; Roudier *et al.*, 2017), an extra error will be included in the determination, the error of prediction. This error shall be considered when deciding on the SOC prediction method applied.

Other emerging and promising techniques are laser-induced breakdown spectroscopy (LIBS) (Senesi and Senesi, 2016; Knadel *et al.*, 2017) and neutron induced gamma-ray spectroscopy (Wielopolski *et al.*, 2010, 2011). LIBS is a cost-effective technique with potential for rapid analysis of elements present in the soil. It has been successfully tested for total carbon measurement in combination with multivariate calibration (da Silva *et al.*, 2008; Belkov *et al.*, 2009) as well as for differentiating organic and inorganic carbon (Martin *et al.*, 2013). Portable equipment is also available (da Silva *et al.*, 2008; Rakovský *et al.*, 2014).

Spectroscopic techniques may be used when technical capacities for adequate chemometric calibration are available. Evidence shall be attached (scientific journals, university theses, local research studies or work carried out by the project proponent) in the corresponding reports, demonstrating that the use of the methodology is appropriate for the agroecological zone were the project is located.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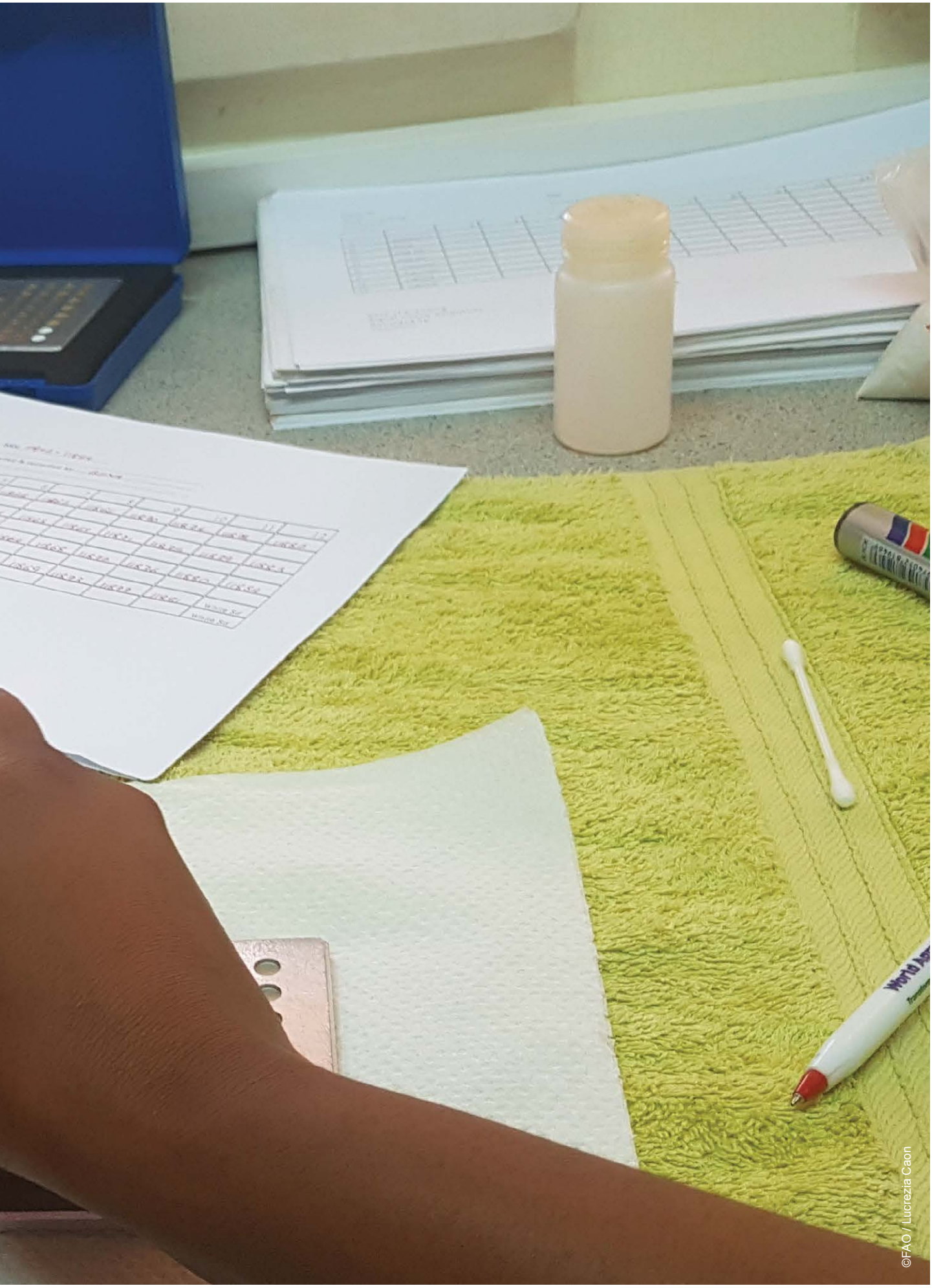

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