SOIL ORGANIC CARBON (SOC) MRV SOURCEBOOK

FOR AGRICULTURAL LANDSCAPES

THE WORLD BANK
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WINROCK INTERNATIONAL

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PURPOSE OF THE WORLD BANK SOIL CARBON SOURCEBOOK

THE IMPORTANCE OF SOIL CARBON IN AGRICULTURAL SYSTEMS

Soils are the largest active terrestrial carbon pool[1], and their ability to sequester and release carbon has direct impacts on carbon emissions to the atmosphere and climate change. Terrestrial land management, deforestation, and the expansion of agriculture and grazing lands have altered the balance between terrestrial and atmospheric carbon pools driving climate change. The United Nations' Food and Agriculture Organization (FAO) estimates that 33% of global soils are degraded,[1] driven by the expansion of systematic food production into natural ecosystems and the unsustainable management of existing soils used to grow crops and raise livestock (Figure 1),[2]or 25 to 40 Mg C/ha, upon conversion from natural to agricultural ecosystems. About 60 to 70% of the C thus depleted can be resequestered through adoption of recommended soil and crop management practices. These practices include conversion from plow till to no till, frequent use of winter cover crops in the rotation cycle, elimination of summer fallow, integrated nutrient management along with liberal use of biosolids and biological nitrogen fixation, precision farming to minimize losses and enhance fertilizer use efficiency, and use of improved varieties with ability to produce large root biomass with high content of lignin and suberin. The gross rate of soil organic carbon (SOC with a quarter of the total degraded land being rangeland.[1]

Productivity losses due to soil degradation in the last century are estimated to be 0.3% per year for croplands and up to 0.2% per year in grazing pastures. [1] While degraded soils are associated with significant greenhouse gas (GHG) emissions into the atmosphere, agricultural and grassland soils have the potential to act as efficient carbon sinks, removing carbon from the atmosphere and sequestering it in the soil. Land management changes needed to conserve current soil organic carbon stocks, reduce soil emissions, and restore soils to their maximum carbon capture capacity are relatively simple when compared with halting deforestation or ceasing the use of fossil fuels. Global agricultural land covers 34% of the Earth's ice-free land surface (2020 estimate[3]), with 12% used as cropland (i.e., land to cultivate food) and 22% as pastures (i.e., land under grazing). About half of the climate change mitigation potential of crops and grasslands comes from soil organic carbon protection and sequestration alone, while an additional 20% can be achieved by reducing other GHG emissions associated to soil management practices.[4]the practical implementation of soil carbon climate strategies lags behind the potential, partly because we lack clarity around the magnitude of opportunity and how to capitalize on it. Here we quantify the role of soil carbon in natural (land-based

Given the large global land area under agricultural management, improved management practices that maintain and increase soil carbon can have a significant impact on global carbon budgets. Restoring soils for carbon capture often has the added benefit of improving soil health while promoting plant growth and increased yields, which in turn has direct positive implications for food security. Feeding the global population is only one of the challenges we will face in our changing climate. Restoring soils in agroecosystems at a scale offers a solution to alleviate food insecurity while reducing carbon emissions to the atmosphere and mitigating climate change.

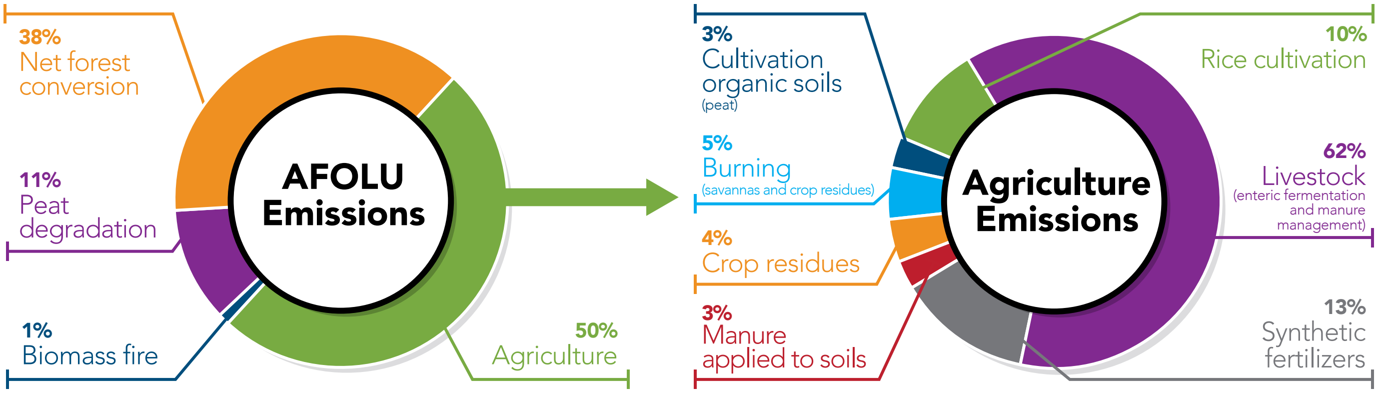

Figure 1. Contribution of different AFOLU sectors to global GHG emissions.[5,6]

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[1] Globally, soils (including peat) account for 2,650 Gt C, whereas vegetation stores up to 650 Gt C.[94]

THE SIGNIFICANCE OF MONITORING SOIL CARBON

Understanding how much carbon is stored in soils and how soil carbon storage changes with management practices is the first step towards making informed decisions about how to improve soil carbon stocks and reduce their degradation and loss. Measuring and monitoring soil carbon not only informs us on its global significance in carbon budgets, but also on soil health and food security and how these can be affected in response to land management practices.

Soil carbon stocks and fluxes are highly dependent on environmental factors such as soil type and slope, climate, or local ecosystems, which in turn respond differently to anthropogenic land use activities. Therefore, global default values may have little accuracy or high uncertainty when applied to estimate soil carbon in local project contexts. Through physical sampling, modeling, or a combination of the two, project managers and agricultural practitioners can estimate current soil organic carbon stocks and monitor changes under different agricultural practices. Monitoring of soil carbon will show how land management impacts soil organic carbon stocks over time and, when paired with sustainable agricultural practices, it can be used in financing frameworks to promote carbon sequestration while supporting livelihoods through increased agricultural yields.

Monitoring changes in soil organic carbon stocks is therefore key to foster investment in sustainable agricultural practices that maintain and increase soil carbon, as well as to incorporate soil carbon sequestration in GHG emission reduction targets at the national (e.g., Nationally Determined Contributions), jurisdictional, and value chain levels. This Sourcebook proposes a framework for soil carbon systems where assessment and monitoring at the project scale align with landscape and jurisdictional scales and with national commitments. Integrating projects into larger strategies to reduce emissions from agricultural settings, such as NDC commitments, requires a thorough assessment of any existing monitoring structures in the agriculture sector in order to determine how to best align approaches and increase cost-effectiveness. Because of the challenges of measuring soil carbon over time, a major constraint to incorporate its monitoring in GHG reporting and financing frameworks has been implementing transparent, accurate, consistent, and comparable methods for measurement, reporting, and verification (MRV) of soil organic carbon changes.[7]to enhance resilience to climate change and to underpin food security, through initiatives such as international '4p1000' initiative and the FAO's Global assessment of SOC sequestration potential (GSOCseq While recent developments in instrumentation and technology are promising, a successful soil carbon MRV system at scale will necessarily include a combination of field and remote measurements and modeling that allows for reliable and cost-effective soil organic carbon assessments. Sustaining soil carbon MRV over time will also allow generating long-term assessments that are extremely valuable to track soil change and emission reductions associated to current and improved soil management practices,[7]to enhance resilience to climate change and to underpin food security, through initiatives such as international '4p1000' initiative and the FAO's Global assessment of SOC sequestration potential (GSOCseq as well as to reduce uncertainty associated with emission factors and to generate robust and cost-effective activity data.

OBJECTIVE AND FOCUS OF THIS SOURCEBOOK

Despite the significant potential of soil to sequester organic carbon, there are challenges to implementing carbon sequestration projects. For example, changes in soil carbon can be relatively small in magnitude per unit area and slow to be fully achieved, while its measurement and monitoring can be difficult and costly depending on the focus of the assessment.

This Sourcebook is designed to provide a conceptual foundation for soil organic carbon measurement and monitoring in croplands and grazing lands or rangelands. It provides methods and simple step-by-step guidance to produce reliable soil carbon measurements across a variety of settings and contexts, with comparisons on what frameworks, approaches, or methods to choose relative to the goal of the assessment, costs, feasibility, and uncertainty.

Greenhouse gas emissions assessments in agricultural settings include direct emissions (i.e., changes in soil carbon, non-CO_2 soil emissions from nutrient amendments) and emissions from consumption of fuel or electricity to manage the crop (i.e., fuel to run farm machinery). Although GHG emissions (e.g., methane, CH_4, or nitrous oxide, N_2O) associated to agricultural land management can be significant and must be assessed to calculate total net GHG reductions of a project, **this sourcebook focuses on soil carbon and specifically changes in soil carbon in agricultural lands that are a direct consequence of land management. It does not focus on emissions from livestock, other than manure application and deposition on soils, or on emissions from agricultural equipment.**

INTENDED USERS

This Sourcebook is intended to serve as a guide for agricultural practitioners and climate change professionals at local, regional, or national scales seeking to leverage the potential of healthy soils to decarbonize the economy, help countries meet their climate targets, and invest in climate-smart agriculture initiatives. This Sourcebook particularly serves as a reference for World Bank agricultural projects to include and report on soil carbon impacts. Projects at the initial design phase can reference this Sourcebook to assist in designing an appropriate soil carbon assessment approach that balances the needs of the project with available methodologies. Projects at the implementation phase that have already selected a carbon assessment approach can also consult this document to identify best practices going forward.

SOURCEBOOK OVERVIEW

After Chapter 1 introduces soil carbon and the agricultural practices that enhance carbon stocks, Chapter 2 presents an overview of how users should select a soil carbon assessment methodology. Chapter 3 is split into modules providing detailed guidance on the decision points related to designing and implementing a soil carbon assessment system based on the needs of the user and the focus of the project**.** Recommendations, case studies, and example calculations are provided throughout the Sourcebook to illustrate how these approaches should, could, or already have been applied in various contexts. The table below outlines the structure of the Sourcebook and the aims of each section.

SECTION	PURPOSE
Chapter 1	
Introduction to soil organic carbon	Provides an overview of the basic abiotic and biotic elements that impact soil carbon.
Effects of agricultural practices on soil carbon	Describes how agricultural practices in cropland and grazing lands can increase both soil carbon inputs and losses, focusing on key activities of crop and grazing management, nutrient management, tillage, and water management.
Incentives to monitor agricultural soil carbon	Outlines the benefits from agricultural soil management, including carbon and non-carbon benefits, and how these could be incentivized through four main payment models: payment for practice, payment for performance or results-based climate finance, payment for practice with performance dividend, and the voluntary or compliant carbon market. Presents Nationally Determined Contributions and how they align with agricultural initiatives.
Chapter 2	
Choosing a soil carbon assessment and monitoring system	Guides the user on how to choose an appropriate soil carbon assessment approach and method based on project purpose or focus of the assessment and resources available by presenting a decision tree, comparisons, and frequently asked questions to further guide decision-making. Provides guidance and key recommendations on how to integrate soil carbon assessments in MRV systems.
Chapter 3	
Module A: Field measurement of soil carbon	Guides the reader on understanding the circumstances where field measurement of soil carbon is appropriate and recommended. Presents best practice field methods to assess soil carbon, laboratory methods to assess soil carbon, and how to design a soil carbon measurement plan, including how to sample soil directly, calculate uncertainty, how to find and select laboratories for analysis, and how to define project area and sampling frequency.
Module B: Soil carbon modeling approaches	Guides the reader on understanding the circumstances where modeling soil carbon is appropriate and recommended. Presents different types of soil carbon models (process-based and empirical models) and when to use them, guidance for the three most common soil calculators using the IPCC model, and guidance on how to choose a process-based model.
Module C: Technology options to supplement soil carbon data	Highlights new advances in technology that can work with or supplement approaches from Module A and B, used to estimate soil carbon through ecosystem carbon flux measurements, in situ ground-based sensors, and remote sensing-based approaches.

Module D: How to develop lookup tables for agricultural practices	Provides readers with guidance on how to develop and use lookup tables as a pragmatic approach to cost-effectively track and report soil carbon impacts, particularly for lookup tables at a country- or region-specific scale, building on previous modules.
Chapter 4	
Implementing the guidance of this Sourcebook	Overview of the importance of measuring and monitoring soil carbon in agricultural settings.
Choosing a soil carbon assessment approach	Review and highlight of the main options to assess soil carbon for a diverse purposes and reporting requirements.
Looking for more in-depth information	Recommendations on next steps to implement the guidance provided by this Sourcebook.
Annexes	
Annex I: Carbon market guidance	Information and guidance for users with examples derived from successfully implemented projects, with step-by-step guidance on how to develop a carbon project for the voluntary market.
Annex II: Carbon market concepts	Overviews key concepts in the carbon project development stage.
Annex III: Resources	A reference to resources that could be helpful when implementing a soil carbon project. These include not all-encompassing lists of relevant agencies, methods, and databases available.
Annex IV: Case studies	In-depth examples of World Bank projects implementing agricultural practices that enhance soil carbon.
Annex V: Glossary of terms	List of used terms with definitions.

CHAPTER 1: SOIL CARBON AND AGRICULTURE BACKGROUND

This chapter provides an overview of the basic elements that drive soil carbon formation and reponses to management practices.

INTRODUCTION TO SOIL ORGANIC CARBON

Soil organic carbon refers to carbon within soils, including fine plant roots, fungi and microbes, and decomposing organic matter from plant litter or animal products such as manure. Soils also contain inorganic carbon in mineral form. The ability of soils to **store (sequester) organic carbon** is determined by the physical structure, or aggregation, of organic and inorganic particles in the soil profile (Figure 2) and the biotic factors driving carbon inputs and outputs to the soil (e.g., living plants, animals, and microorganisms that inhabit the soil). Physical and biotic factors change with depth (with upper soil layers closer to the surface more influenced by the environment) and with land use and management practices

BOX 1.1 IMPORTANCE OF SOIL STRUCTURE

Soil inorganic particles – broadly classified as sand, silt, and clay – are bound to each other and to soil organic components in the soil, forming **aggregates or clusters of aggregates** of different size, porosity, and permeability that define the soil's structure. Aggregation is known to protect organic matter, making it less accessible (physically and biologically) to decomposition and loss.

Clays are the smallest particles in the soil. When clay content is very high, issues of reduced soil porosity or severe compaction can often occur, having detrimental effects on crop growth and limiting soil carbon sequestration potential. Clays, however, can bind strongly to organic particles, retaining them in the soil and slowing their decomposition. Sandy soils are naturally more porous because of the large size of sand particles, facilitating microbial access to organic matter and thus favoring the decomposition of plant litter, or facilitating quick draining and leaching of soils, showing low soil carbon retention abilities.

Because of the interactions of geological, biological, and climate features over time, the soil is composed of layers, each with a distinct texture and composition. These layers are called **soil horizons.** The vertical profile of soil horizons can vary geographically, yet they are generally as follows (Figure 2):

O- Organic layer: found on the top of soils made almost entirely of leaf litter, undecomposed plant matter, and humus (decomposed organic matter).

A- Topsoil: mineral soil with high concentrations of carbon and microbial activity, integral to plant growth.

B- Subsoil: soil with high mineral content accumulated from leaching of the above layers. Minerals lock carbon.

C- Unconsolidated layer: made from weathered or decomposed rock.

Most soil carbon is found in the organic and topsoil horizons. Natural soil profiles vary in the thickness of each horizon due to processes of soil formation and the way the soil is managed. Improper management can lead to high levels of soil erosion, which strips the carbon from topsoil horizons and makes it more difficult for soils to accumulate additional carbon. Improper management can also lead to soil compaction, which has a detrimental impact on plant growth and soil microbial communities, leading to lower carbon sequestration.[2,8]

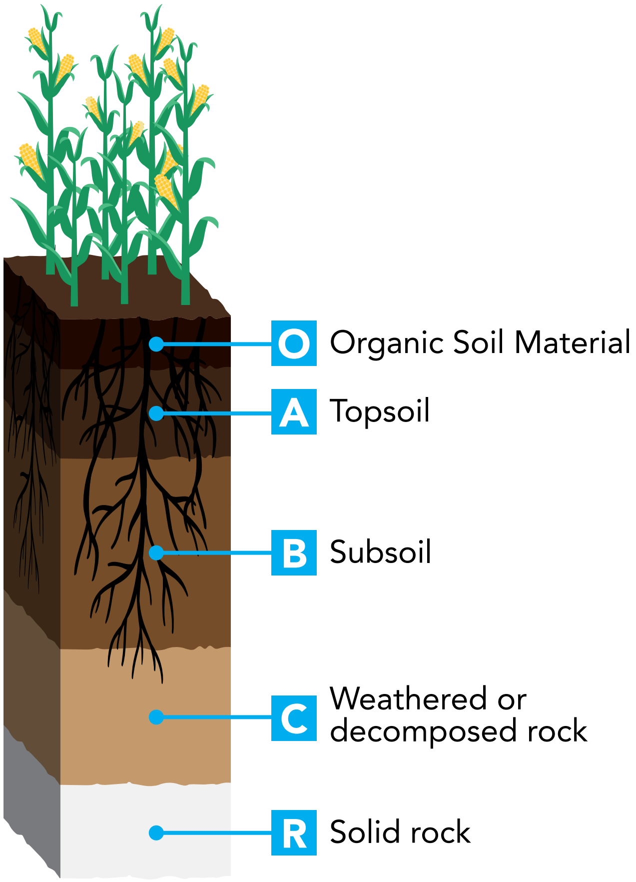


Figure 2. Typical soil profile

SOIL CARBON CYCLE

Plants absorb carbon dioxide (CO$_2$) from the atmosphere through photosynthesis, transforming carbon into plant structures (i.e., biomass) and releasing organic compounds into the soil through root exudates. This stimulates soil microbial and fungal growth. In exchange, these vibrant microbial communities facilitate plant absorption of valuable nutrients from the soil, such as nitrogen.

As plant materials are lost and plants ultimately die, their remnants are decomposed by microorganisms, making up a heterogenous mixture of plant litter and organic matter in different stages of decomposition. During the decomposition of organic matter, carbon dioxide is released back into the atmosphere. A significant proportion of that carbon remains in the soil, stored within the microorganisms and the decaying matter. Through this process, organic remnants in the soil become more difficult to decompose and accumulate in the soil profile, remaining stored for long periods of time if the soil remains undisturbed. Because most organic inputs to the soil come from plants at the soil surface and subsurface, organic matter is typically higher in the upper soil layers and decreases progressively with depth unless there is mobilization of soil compounds to deeper layers.

The soil can act as a carbon sink or source, depending on the balance between soil carbon accumulation and soil carbon losses (Figure 3). Climatic variables and management affect soil carbon sequestration rates and the amount of time carbon stays in each part of the cycle (**residence time**), from leaf litter to organic remnants in different stages of decomposition.[8]993 to 0.5-m, and 1,505 to 1-m depth. Thus, ~55% of SOC to 1-m lies below 0.3-m depth. Soils of agroecosystems are depleted of their SOC stock and have a low use efficiency of inputs of agronomic yield. This review is a collation and synthesis of articles published in peer-reviewed journals. The rates of SOC sequestration are scaled up to the global level by linear extrapolation. Soil C sink capacity depends on depth, clay content and mineralogy, plant available water holding capacity, nutrient reserves, landscape position, and the antecedent SOC stock. Estimates of the historic depletion of SOC in world soils, 115–154 (average of 135 Warm humid climates tend to have larger populations of active microbes which break down SOC. Therefore, soils in cold climates often have higher rates of sequestration and a longer soil carbon residence time.[9] On the other hand, when soils are fully saturated in water for long periods of time, anaerobic conditions (i.e., with no oxygen) are created. Microbes are therefore not able to efficiently break down organic components and carbon is locked away. This is clearly shown in peat soils, formed from partially decomposed plant materials due to long-term soil saturation. Carbon residence time is extremely difficult to measure outside research-intensive sites (e.g., academic studies). It is well known, however, that while difficult to decompose plant materials (like woody materials) generally have longer residence time in the soil than other less complex materials, organic matter decomposition is a microbially mediated process and thus environmental and biological factors control the time carbon stays locked in the soil.[10] Management practices that degrade the soil would therefore decrease soil organic carbon residence time and thereby increase carbon losses.

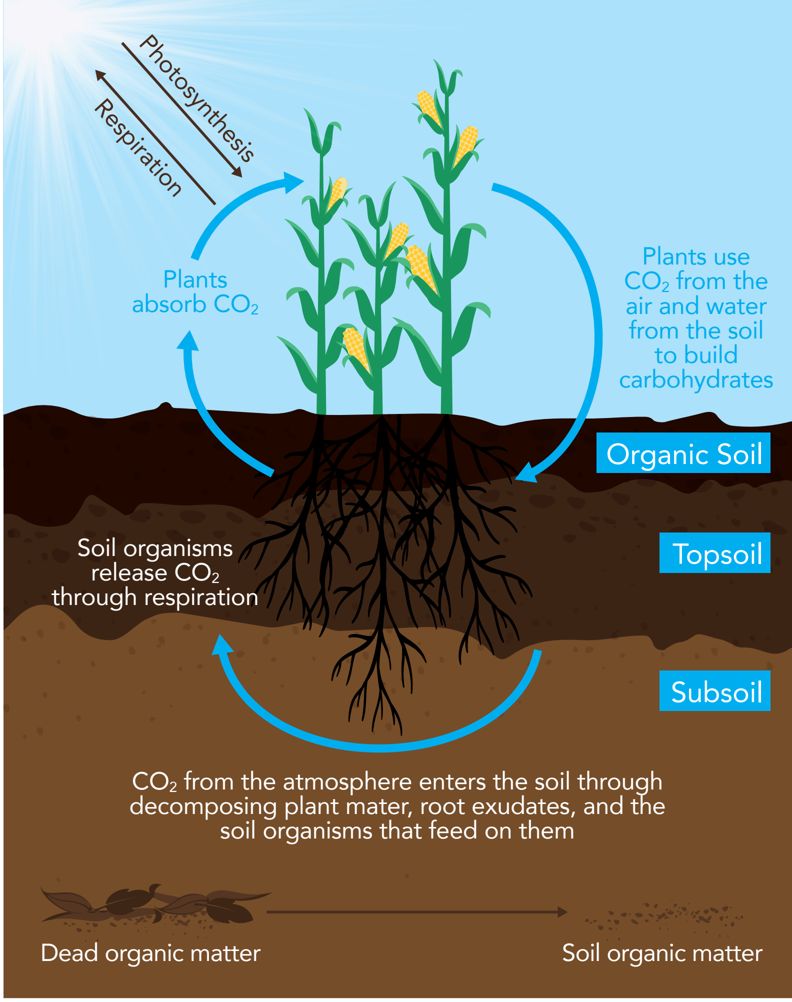


Figure 3. Basics of soil organic carbon cycling

Management directly affects the carbon cycle and sequestration within soils, dictating whether the soil is a source of carbon to the atmosphere or a sink.[11,12] Practices that disturb soils, such as tillage, can expose stores of carbon to oxygen in the air which, in the short term, increases microbial activity, leading to a breakdown of soil organic carbon and an ultimate reduction in the microbial population. On the other hand, increasing the woody biomass in soils can increase soil carbon sequestration as woody structures are rich in complex organic components that take longer to break down than herbaceous vegetation. The next section explains the effects of agricultural management practices on SOC in more detail.

IMPACTS OF AGRICULTURAL PRACTICES ON SOIL CARBON

Agriculture significantly impacts soil carbon. Soil organic carbon is 25-75% lower in cropland and intensively grazed grassland soils compared to equivalent undisturbed or natural ecosystems.[12] As a result, the expansion of agricultural lands throughout history has resulted in carbon losses of 40-90 Gt C.[1] Croplands and grazing lands are of high importance in global carbon cycles because of their extent, significant soil organic carbon stocks, and frequent state of intensive environmental pressure due to degradation or unsustainable management (Table 1).[13–15] Agricultural practices can alter soil moisture, respiration rates, microbial processes, erosion levels, mineralization rates, and organic matter, all of which play roles in impacting sequestration or losses of soil carbon. Low soil carbon can reduce crop and grazing land productivity and it is therefore essential that we understand it from both a climate change and a food security perspective.[12]

Table 1. Global carbon stocks of the world's biomes in vegetation and soil carbon pools down to the top meter of depth.[15] Note: Although these estimates are from 2000 and have high uncertainty due to ambiguous biome definitions, it provides a useful overview of the magnitude of global carbon stocks in terrestrial biomes.

Biome	**Global carbon stocks (Gt C)**		
	Vegetation	**Soil (top 1-m)**	**Total**
Tropical forests	212	216	428
Temperate forests	598	100	159
Boreal forests	88	471	559
Tropical savannas	66	264	330
Temperate grasslands	9	295	304
Deserts	8	191	199
Tundra	6	121	127
Wetlands	15	225	240
Croplands	3	128	131
Total	**466**	**2,011**	**2,477**

SUSTAINABLE SOIL MANAGEMENT

Farmers can adopt sustainable land management practices to reduce the impact of cropland and grazing land management on soil carbon and maintain soil fertility. These sustainable approaches focus on three main techniques to minimize agricultural impacts on soil carbon:[16–18]

1. reducing soil carbon losses, avoiding or reducing practices that lead to decomposition and erosion;
2. increasing the sequestration of soil carbon, which actively increases the removal carbon from the atmosphere; and
3. conserving soil carbon stocks, a "least-cost opportunity" approach based on a combination of practices that reduce soil disturbance and maintain an adequate vegetative cover.

The World Bank sees the sustainable soil management agenda at the core of achieving its climate change goals and is scaling up investment on climate-smart agriculture through its Climate Change Action Plan. In 2020, 52% of the World Bank's agricultural finance targeted climate change mitigation and adaptation through the support of agricultural producers and the dissemination of climate-smart agricultural technologies, including sustainable soil management.

The effects of agricultural management practices on soil organic carbon are dynamic and often impact multiple steps in the carbon cycle depending on the specific practices and ecological circumstances. Changes to the inputs to or losses from an agricultural system will influence the soil carbon pool (Figure 4).

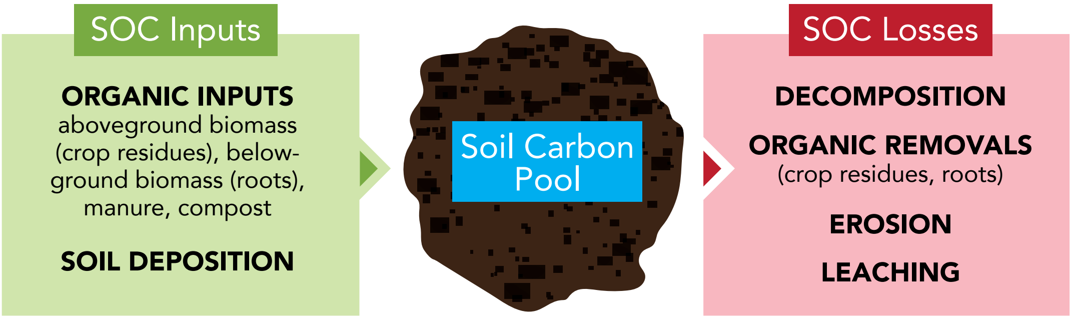


Figure 4. Soil carbon stock in an agricultural system depends on carbon inputs and losses. The balance of the two will determine impacts on the existing carbon pool.

Overarching frameworks that exemplify sustainable soil management include regenerative agriculture, climate smart agriculture (CSA), regenerative or improved grazing, and conservation agriculture, all of which aim to promote economic and climate resilience. Specific soil management practices promoted under these frameworks can be grouped as activities that:

- Reduce soil disturbance,
- Maintain or regenerate soil cover, and
- Maximize plant and soil biodiversity.

These sustainable soil management practices increase soil carbon and overall soil health while reducing soil carbon losses. Their soil carbon benefits compared to non-sustainable practices are described in more detail below, with a focus on cropland and grazing land agro-ecosystems. See Case Study 1.1 for an example of the emission impacts of sustainable farming techniques.

Sustainable soil management, *as defined by the World Soil Charter, includes soils where "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."* [95]

Case study 1.1: Climate Smart Agriculture (CSA) for major staple crops in China

The World Bank's Climate Smart Staple Crop Production Project (2014-2020) promoted CSA in several counties in China. The project focused on rice, corn, and wheat cropping systems, providing financial and technical support to over 19,000 farmers' households in 30 villages. A variety of Climate Smart Agriculture practices such as low and no-tillage practices, optimized nutrient and fertilizer inputs, mulching, and crop rotation, as well as improved water management practices for rice production, were implemented. By implementing these crop production practices over 24,750 hectares, the project has reduced emissions by 23,732 t CO_2e and sequestered 71,683 t CO_2e in soil carbon.

KEY CROPLAND AND GRAZING LAND SUSTAINABLE MANAGEMENT PRACTICES

Key commonly applied sustainable practices include no-till agriculture, the application of crop residue or mulch, crop and grazing rotation to reduce pressure on the soil, intercropping or mixed cultivation, conservation agriculture, and application of manure or compost (Figure 5). These management practices interact and are often most effective when paired.[19] Because soil carbon sequestration occurs non-linearly, the effects of these management practices on soil health may only be visible over a medium or long term (e.g., ten to a hundred years). For example, the International Panel on Climate Change (IPCC) guidelines assume that soil carbon levels reach an equilibrium over a default period of 20 years, explained further in Chapter 2.

This section provides an overview of the most common sustainable management practices in agricultural settings and how they affect directly and indirectly soil carbon stocks.

Practices that increase soil carbon inputs

NUTRIENT MANAGEMENT

- Integrated use of chemical fertilizers
- Compost/manure
- Crop residues/mulch
- Biochar

VEGETATION COVER MANAGEMENT

- Crop rotation
- Cover crops
- Managed fire
- Mixed cultivation, agroforestry

Practices that decrease/avoid soil carbon losses

WATER MANAGEMENT

- Reducing evaporation
- Reducing runoff
- Irrigation

TILLAGE MANAGEMENT

- No-till
- Reduced till

GRAZING MANAGEMENT

- Rotational grazing, regenerative grazing
- Reduction of livestock grazing hours

Figure 5. Common management practices that impact soil carbon in croplands and grazing lands. Note that some of the practices in this figure act on different points in the soil carbon cycle and therefore may increase carbon inputs as well as decrease losses. For simplicity, they have been grouped into the relevant dominant category. Conservation agriculture is not directly mentioned because it entails a combination of multiple practices already described here.

Crop and grazing management

Cropland and grazing land management regulates above- and belowground biomass inputs, depending on the type(s) of crop(s) cultivated, the frequency of cultivation, the inclusion of trees in the agricultural landscape as agroforestry, the period of soil surface coverage, and grazing intensity. In some agroecosystems, crop and grazing rotation and management techniques have a greater impact on soil carbon sequestration than nutrient/fertilizer inputs,[20] although the net impact of these management techniques is highly dependent on the overall system of implemented practices[17,21] (Figure 6; see Case Study 1.2 and Case Study 1.3).

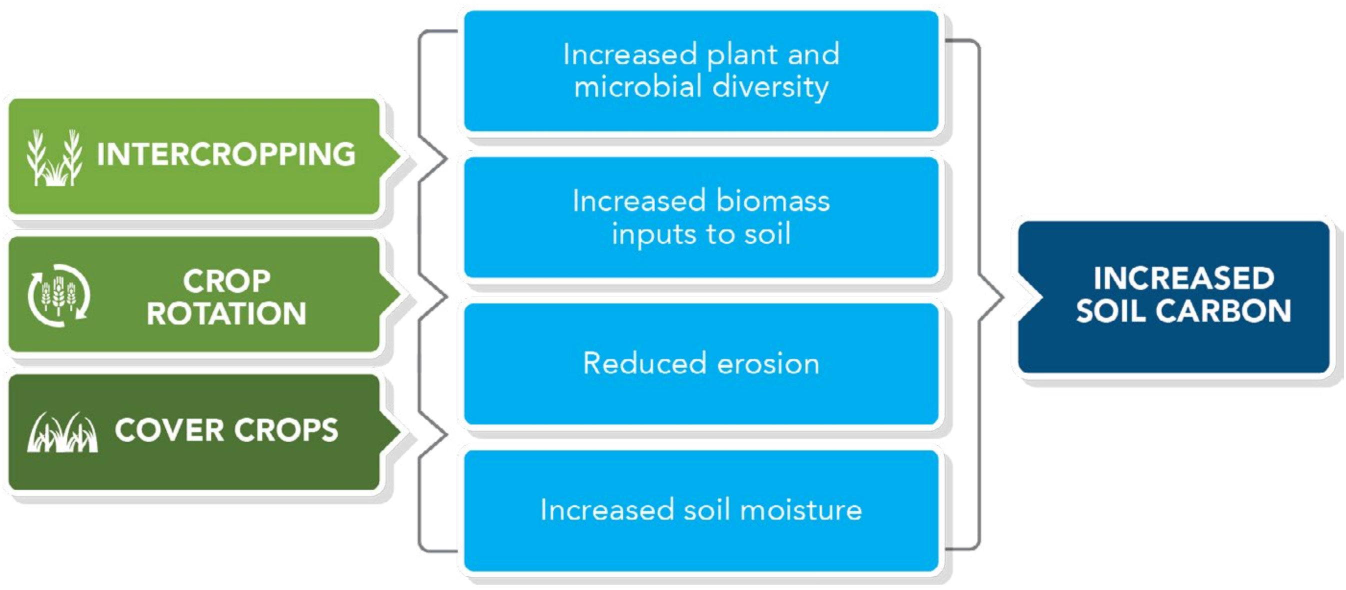


Figure 6. General impacts of common crop management on soil carbon

Case Study 1.2: Agroforestry systems

Agroforestry involves the integration of trees or shrubs in agricultural land as live fences, wind breaks, alley farming, shade farming, silvopasture, or other techniques. The conversion of conventional agriculture to agroforestry has been shown to increase SOC stocks up to 40% in the top meter of soil, with results highly dependent on site-specific context.[96]having the ability to sequester atmospheric carbon dioxide (CO2 Agroforestry in the form of silvopastoral systems (SPS) was implemented as part of the World Bank's "Mainstreaming Sustainable Cattle Ranching" project in Colombia (2010-2020).[97] The project converted 38,390 ha of degraded open pastures into SPS areas interspersed with trees, shrubs, and fodder crops. The project ultimately sequestered an estimated 945,795 t CO_2e in SPS in both soil carbon stocks and aboveground biomass.[97]

While grazing can be positive to vegetation productivity and root turnover in grasslands, overgrazing leads to deteriorated soils and carbon losses (Figure 7; Case Study 1.3). Similar to croplands, rotational and regenerative approaches exist to allow for soil carbon and vegetation recovery. The number of grazing hours in the field can also be reduced to control livestock impact. When possible, vulnerable areas such as riparian zones should be protected from cattle grazing.

Managing crops and grazing lands with periodic fires can increase vegetation productivity while soil organic carbon is either maintained or reduced.[22] The combustion process, however, generates significant GHG emissions.

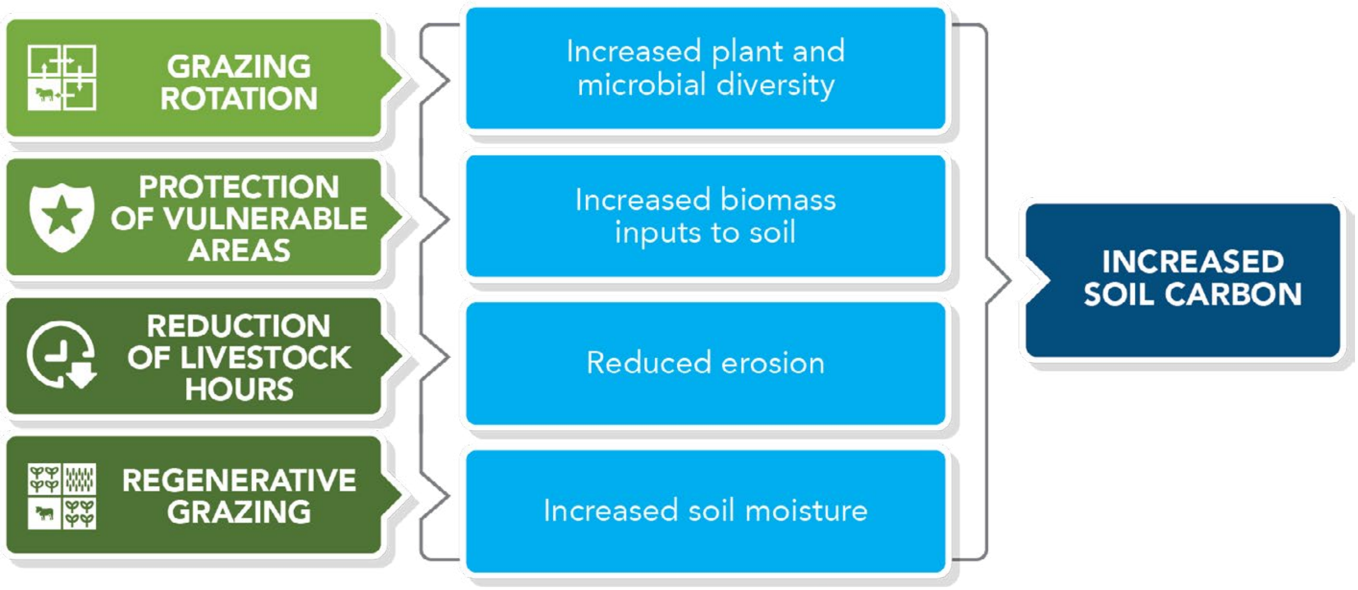


Figure 7. General impacts of common grazing management on soil carbon.

Case Study 1.3: Impact of grazing intensity on soil carbon in grasslands

The impacts of grazing on soil organic carbon are highly dependent on the abiotic and biotic context of the grazing system. Heavy grazing in the semiarid steppe ecosystem of northern China significantly deteriorated topsoil carbon due to animal trampling, reduced organic matter input, less root growth, and greater susceptibility to erosion.[98] The effects of grazing lasted long-term, with no improvements even after years of ceasing grazing. In contrast, a study of grazing in Uruguay found that belowground biomass and primary production were higher in grazed than un-grazed areas, resulting in greater carbon sequestration due to higher root turnover in grazed areas.[99] The rate of carbon sequestration in grasslands is known to be highly dependent on agro-ecological conditions and farming regimes, with sequestration typically outweighed by emissions from grazing.[100] The protection of current carbon stocks in grasslands, however, is of key importance, as soil organic carbon can be lost much faster than it accumulates.

Nutrient Management

The application of nutrients is critical in many cropland and grassland systems to improve yields. Nutrient management involves the application of chemical fertilizers (usually containing varying ratios of nitrogen, potassium, and phosphorus, i.e., NPK) and/or organic fertilizers and amendments, such as compost, manure, crop residues/green manure, or biochar. Grazing management and animal movement (i.e., pastoralism) is also key in the management and redistribution of nutrients in grazing lands, as fertilization from livestock manure in grazing systems can also contribute to changes in soil carbon. The effectiveness of adding organic matter can vary greatly: biochar for example mineralizes 10–100 times more slowly than fresh crop residues[11], staying within and stabilizing the soil carbon pool. Nutrient application often increases soil carbon both directly (through the addition of organic matter) and indirectly (by increasing net primary productivity and therefore providing additional biomass inputs; Figure 8). It is key to optimize nutrient management and use fertilizers efficiently to limit the generation of GHG while maintaining agricultural productivity.[23]

Chemical fertilization: *When paired with other crop management techniques and used judiciously, the application of chemical fertilizers can improve carbon stocks. However, excessive application can stimulate soil respiration, resulting in a decrease in soil carbon stocks and degradation of overall soil quality.*

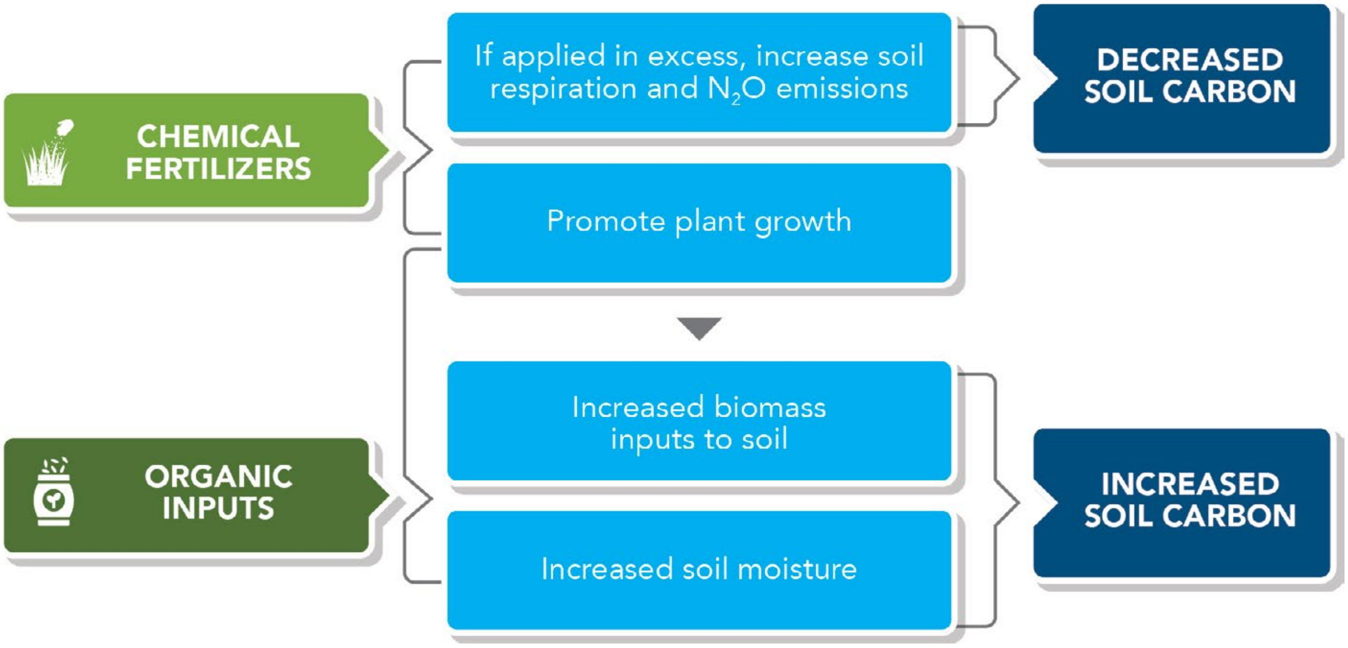


Figure 8. General impacts of nutrient management on soil carbon

Case Study 1.4: Applying crop residues in Zimbabwe

Studies from Asia, Latin America, and Africa have shown that retaining or applying crop residues to agricultural plots has benefits for soil quality, soil carbon, soil moisture, nutrient cycling, and erosion.[101] For example, a study of maize cropland in Zimbabwe found that after nine years, sandy soils in which crop residues were retained had 42% more organic carbon than soils in which residues were removed by "clean ripping" between rows of crops.[102] The study suggests that carbon inputs in the form of crop residues have a significant impact on soil carbon. However, the soil type played a key role in how carbon stocks were affected.[102]

Tillage

Tillage has a significant impact on soil carbon in agricultural systems (Figure 9).[24] It removes vegetation cover and disturbs the soil surface, aerating the soil and breaking soil aggregates, leading to a chain reaction that disrupts soil organic carbon levels, especially in topsoil. The most appropriate tillage technique to choose will vary widely by crop, ecosystem, soil type, and other agricultural practices implemented. In some systems, tillage can be eliminated (i.e., become no-till systems) or can be reduced by changing tillage intensity, depth, or time involved.

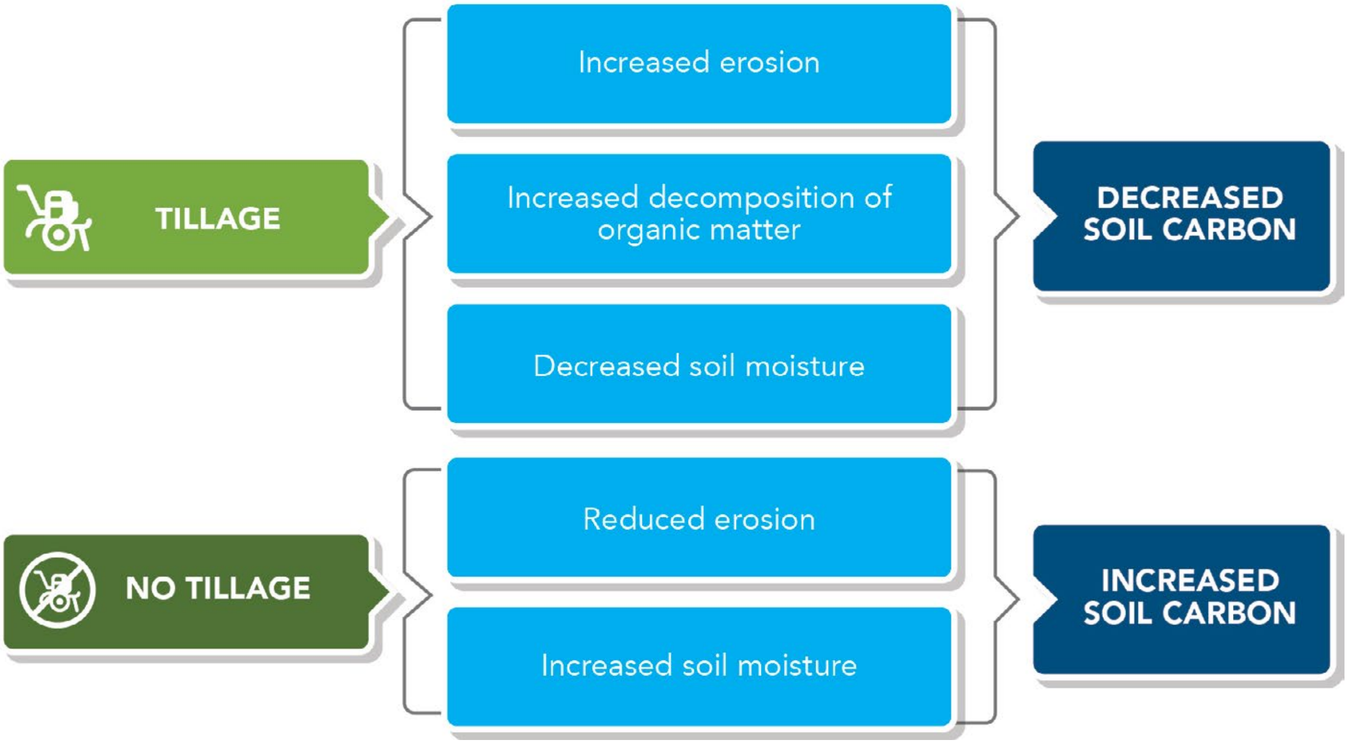


Figure 9. General impacts of tillage on soil carbon

Case Study 1.5: Expansion of zero tillage approach in Brazil

Brazil's soils are particularly susceptible to erosion due to intense rainfall.[103]particularly in tropical and subtropical areas. The development and adoption of Zero Tillage Conservation Agriculture (ZT/CA Since the 1970s, Brazilian farmers have been slowly transitioning away from traditional inversion tillage, adopting a zero-tillage approach in approximately 32 million ha of land in 2013.[103]particularly in tropical and subtropical areas. The development and adoption of Zero Tillage Conservation Agriculture (ZT/CA An additional 8 million ha of cropland under zero tillage in Brazil would sequester approximately 8 Tg C per year in soils over the first 10-15 years.[104] The Brazilian government has introduced policies and programs to encourage CSA and conservation tillage. For example, through the "Low Carbon Agriculture (ABC)" program, the government provides low interest credit to farmers adopting CSA in order to improve agricultural efficiency and reduce climate impact.[105] Studies have shown that zero tillage agriculture in Brazil conserves soil carbon,[104,106,107,108] capturing up to three times more carbon than under conventional tillage over a 20 year period.[107]

Water management

Maintaining soil moisture can impact soil carbon by reducing erosion, increasing biomass inputs, optimizing soil respiration, and decreasing SOC loss. Water management practices include more effective irrigation techniques as well as approaches to minimize evaporation and reduce the loss of soil carbon through runoff (Figure 10). Irrigation techniques such as drip irrigation, sub-irrigation, or precision application could help to achieve this, as could runoff management through windbreaks, contour cropping, strip contour cropping, terracing, grassed waterways, or slope barriers. Reducing evaporation to maintain soil moisture can be accomplished through applying green manure or mulch, integrating trees in croplands and grazing lands to provide shade, or reducing tillage.

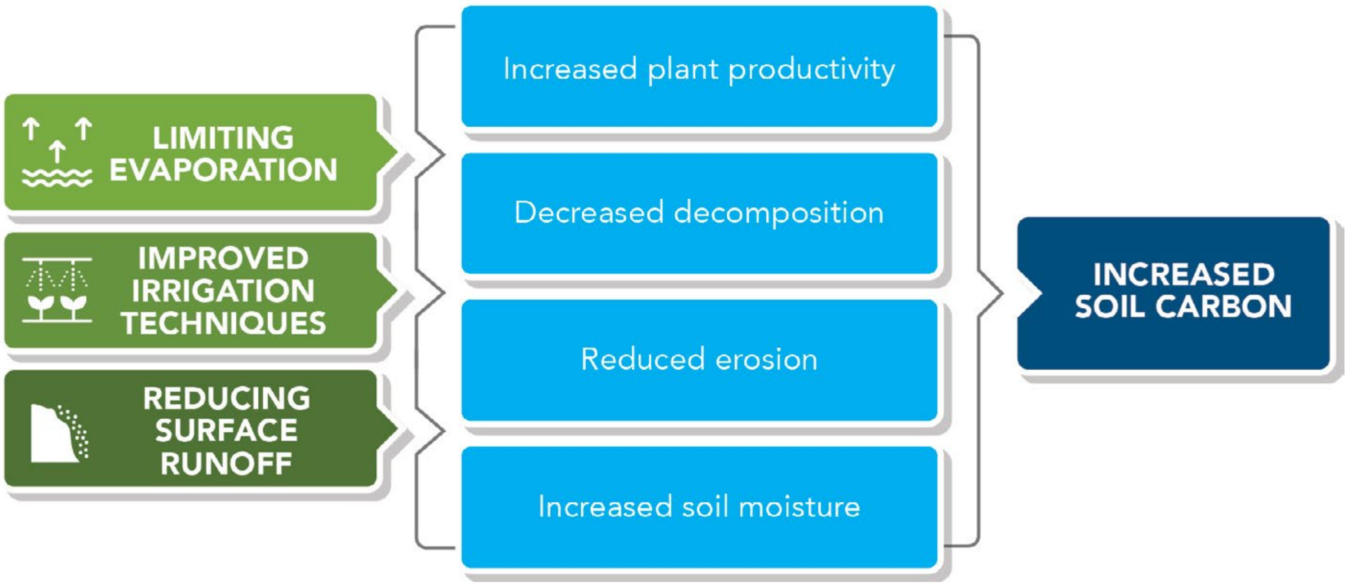


Figure 10. General impacts of water management on soil carbon

Case Study 1.6: Impact of soil irrigation management on soil carbon in agricultural fields

The irrigation method used on a plot influences runoff and thus the loss of sediments, nutrients, and SOC, particularly when combined with other soil eroding practices like deep tillage. A study in furrow-irrigated cropping systems revealed that a 60-90% decrease in runoff was associated with a 65-83% reduction in carbon export from the field. [109] The loss of dissolved or particulate carbon in runoff has been correlated with changes in soil carbon stocks, as irrigation can increase aggregate stability and result in a 3-30% increase in soil carbon content, depending on the soil type.[110,111] Excessive irrigation or flood irrigation, on the other hand, can result in carbon increases that could be offset by the production of GHGs from organic carbon decomposition under limited oxygen conditions and by an increase in dissolved carbon from the soil surface into the water column.[112]

INCENTIVES TO MONITOR AGRICULTURAL SOIL CARBON

BENEFITS OF AGRICULTURAL SOIL MANAGEMENT

There are many incentives to conserve and restore soils, spurred by the financial, social, and environmental benefits doing so provides. Carbon benefits generate payments for emissions reductions or increases in sequestration. Assessment and monitoring of carbon benefits generated by a carbon project can be integrated with national approaches (such as Nationally Determined Contributions [NDCs] and National Inventory Reports [NIRs]). Aligning project-level soil carbon monitoring with existing monitoring structures can allow for a systematic implementation of climate action plans and may open doors to other forms of investments.

Carbon benefits

As the largest terrestrial carbon pool, soils have a key role to play in climate change mitigation. Approximately 50% of the mitigation potential of crops and grasslands comes from just soil organic carbon conservation and sequestration, while another 20% of this mitigation potential is associated with GHG emissions from other gases associated with soil management practices.[4]the practical implementation of soil carbon climate strategies lags behind the potential, partly because we lack clarity around the magnitude of opportunity and how to capitalize on it. Here we quantify the role of soil carbon in natural (land-based Degraded agricultural soils can be restored and maintained through the sustainable management techniques discussed above, increasing sequestration or leading to emissions reductions. Such emission reductions or enhanced carbon storage may allow land managers to leverage finance from entities in the private sector, civil society, multilateral funders, or buyers in the carbon market seeking to offset emission, as well as potentially contributing to NDCs and other existing MRV frameworks, and s.

Non-carbon benefits

Along with these carbon benefits, sustainable agricultural practices that increase soil carbon could also contribute to improved adaptation and resilience, increased yields, reduced poverty, improved gender balances, and healthier ecosystems. For example, conservation agriculture through the Total LandCare project in Malawi and Zimbabwe has increased groundnut and cereal yields as well as promoted soil health, while agroforestry projects through the Congo Basin Forest Fund have provided sources of fuelwood necessary for cooking and heating, reducing nearby deforestation.[25] These co-benefits may also contribute to non-monetary aspects of benefit sharing discussed below.

Sustainable practices could also give farmers access to premium markets (e.g., stacked benefits markets) through sustainable certifications that allow farmers to sell produce at a higher premium. This is the case for organic and fair-trade produce, sold in markets at a higher price than conventional produce because of sustainability implications. In addition to financing soil carbon sequestration under these sustainable agricultural management practices, buyers or sponsors in the public, private, and multilateral sectors can include these types of stacked benefits in their benefit-sharing agreements with landowners. These options are further explored in Chapter 2.

BOX 1.2 STAKEHOLDER ENGAGEMENT

Initiatives to address NDCs or receive payments by reducing GHG emissions in the agriculture sector will require stakeholder engagement to be successful. The non-carbon project co-benefits, especially the potential for increased yields, improved livelihoods, and greater nutrition, act as incentives to engage stakeholders. Relevant stakeholders could encompass government, research organizations, civil society, the private sector, and local communities/farmers:

- The government usually regulates and manages the program and provides broader infrastructure, and at a local level could also support implementation.
- Research organizations develop protocols and tools for soil organic carbon measurement and assessment.
- Civil society supports farmers with training and advisory services, develop projects, and provide feedback on soil carbon accounting systems, while the private sector could act as an important funding source or could be owners of project areas.
- Local communities and farmers are at the heart of any project, and some standards (such as the Verified Carbon Standard [VCS]) require local stakeholder consultation and ongoing communication as part of their verification process.[140]

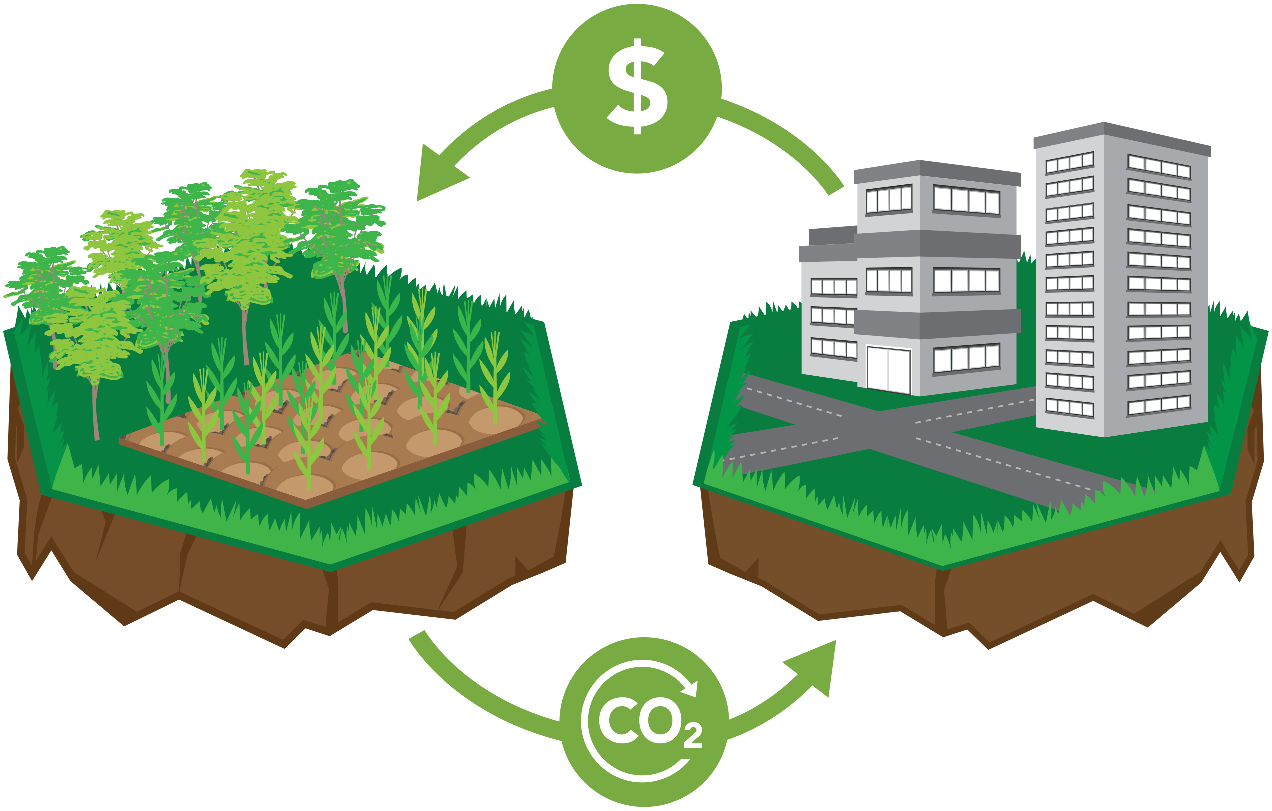


Figure 11. Flow of payment scheme

PAYMENT MODELS FOR AGRICULTURAL SOIL CARBON BENEFITS

Soil carbon in agroecosystems has gained international attention due to its relevance to food security and climate change mitigation and adaptation. Because soil organic carbon is both an indicator of soil health and a predictable and measurable outcome of sustainable agroecosystem management, projects and practices that reduce emissions, increase carbon, or conserve carbon in agricultural settings can be incorporated into various payment models.

Different payment systems to conserve soil carbon through agriculture have emerged, promoting the generation of sustainable livelihoods through positive and conditional incentives that are intended to preserve or improve the environment while also contributing to the alleviation of poverty.[19,26]intermediate and passive These approaches can therefore facilitate the adoption of practices that contribute to enhancing soil health and soil organic carbon and can be a form of payment for environmental services (PES). Payment models could focus on conserving soil carbon, reducing emissions from soil carbon, or increasing sequestration of carbon into soils.
There are four broad types of payment systems applicable to projects sequestering soil carbon in agricultural settings, listed in increasing order of complexity, cost to implement, and confidence of atmospheric impact:

1. Payment for practice;
2. Payment for practice with performance dividend
3. Payment for performance or results-based climate finance (RBCF); and
4. Carbon market, voluntary or compliance.

The applicability and comparison of these four options for projects sequestering soil carbon in agricultural settings are described in Table 2, with details on how to develop a carbon project for the voluntary market provided in Annex 1.Attributes of successful soil carbon-based payment schemes include:[19,26,27]intermediate and passive

- generating additional soil carbon benefits that would not be achieved in the absence of payment or project implementation,
- eliminating the incentive to revert implementation of soil organic carbon enhancing practices and guarantee long-term permanence of carbon benefits generated, and
- preventing soil carbon degradation beyond the focus farm(s), i.e., avoiding displacement or leakage of emissions.

Benefit-sharing mechanisms

Benefit sharing refers to the distribution of revenue from payments made for emissions reductions or sequestration, and could include non-monetary benefits (e.g., community development, biodiversity).[28] The design and implementation of a benefit-sharing mechanism should be efficient and transparent to incentivize stakeholder participation and support, and must be developed based on unique project conditions and outcomes of local consultations with project beneficiaries. A benefit-sharing agreement would also include conditions to ensure implementation and permanence and to lay out requirements in cases of non-compliance.

Benefits could go to those with legal rights to the land who may have experienced opportunity costs (i.e., local communities) or those incurring project implementation, monitoring, and administrative costs (i.e., project developers).[28]

Existing local legal frameworks can be integrated within project benefit-sharing agreements, which can reduce the need to establish and operate new institutions.

Recommendation: To protect soils and ensure project permanence, policymakers, project managers, and communities should also explore approaches other than payments for carbon benefits. For example, securing land access and land tenure rights, providing access to financial and technical resources for CSA, and promoting education and training for sustainable agricultural management could all be effective ways to increase area under sustainable agricultural management and subsequently increase soil carbon. Grants and donors could finance such initiatives.

Table 2. Comparison of payment models that can be applicable to projects sequestering soil carbon in agricultural settings, listed by increasing complexity, cost to implement, and confidence of atmospheric impact (i.e., emission reductions or enhanced sequestration).[26,29]

Payment type	Description	Advantages	Disadvantages
i. Payment for practice (input-based system)	Fixed payments per area under a practice implementation agreement. ***Example***: *a project that implements conservation agriculture is paid per hectare or to cover the cost of implementation; see case study box 1.7 below.*	• Partial payments can be advanced to encourage participation. • Low monitoring and validation costs. • Relatively easy to implement. • Payments do not reflect market value of carbon (could be a disadvantage if market price is high).	• Actual carbon benefits generated are approximated (low site-specific accuracy). • Payments can be based on political priorities instead of environmental benefits. • Strict commitment to agreed-upon practices/land use, regardless of site-specific factors.
ii. Payment for practice with performance dividend	Hybrid between payment for practice and payment for performance. Users are paid for the practice, but monitoring occurs at the program level and additional payments are made where the program is successful in carbon metrics. ***Example:*** *a low-till initiative at a community or watershed level pays each farmer implementing low-tillage, but the program receives additional payment after demonstrating successful results across the entire community/watershed and this payment is distributed among participants.*	• Relatively easy to implement. • Practice payments do not reflect market value of carbon (could be a disadvantage if market price is high). • Incentive to perform. • Direct estimation of carbon benefits. • Transparent.	• Practice payments can be based on political priorities instead of environmental benefits. • Carbon payments received after performance. • Potentially costly monitoring is required to estimate carbon benefits.
iii. Payment for performance (output-based system)	Payments based on tons of carbon losses reduced and/or tons of carbon sequestered, compared to the scenario without project implementation (baseline). Payments follow pre-agreed conditions and are based on basic indicators for performance. High accuracy is not required. ***Example***: *a large agricultural corporation funds an insetting project to promote conservation agriculture within its own supply chain, paying per ton of carbon sequestered without relying on a carbon market.*	• Incentive to perform. • Direct estimation of carbon benefits. • Transparent. • "Guarantees" additionality. • More basic indicators and accounting than carbon markets.	• Costs or inputs to perform are not considered. • Payments received after performance. • Potentially costly monitoring is required to estimate carbon benefits. • Verification costs. • Excludes already sustainable farms.

iv. Carbon market	Payments based on tons of carbon losses reduced and/or tons of carbon sequestered, compared to the scenario without project implementation (baseline), following approved methods t and requirements more strict than those for payment for performance output-based system. Payments based on market value of carbon. ***Example****: an agroforestry project verified by a carbon market such as Plan Vivo or VCS to produce and sell carbon credits.*	• Accurate estimate of carbon benefits. • Transparent. • "Guarantees" additionality. • Payments reflect market value of carbon (could be a disadvantage if price is low). • Additional activity co-benefits with can attract carbon offset buyers.	• Costs or inputs to perform are not considered. • If decreases in productivity occur, they can lead to leakage. • Accurate and therefore often costly monitoring is required to estimate carbon benefits. • Verification costs. • No incentive for farms that are early adopters of good practices. • Often cost-prohibitive to smallholders if external support is lacking. • Payments tied to credit purchase.

Case Study 1.7: Eco-schemes as a payment for practice model in the European Union

Eco-schemes are agricultural payment schemes incentivizing activities related to climate, environment, animal welfare, and antimicrobial resistance. They were introduced in the European Union in 2018 as part of the Common Agricultural Policy (CAP) and will contribute to achieving the EU's Green Deal Targets.[113] Funded by the EU, eco-schemes will provide annual payments to farmers implementing agroecology, agroforestry, organic farming, carbon agriculture, improved nutrient management, and other environmentally beneficial practices. Payments are provided in two ways that can be considered as payment-for-practice, depending on local managing authorities: either a) basic income support based on the actual or expected results to be achieved or b) covering costs incurred and income foregone as a result of implementing practices.[113]

NATIONALLY DETERMINED CONTRIBUTIONS

NDCs are key tools to achieve the targets outlined in the Paris Agreement and the goals specified in each NDC could encourage funding for soil carbon projects. NDCs are national strategies to address climate change, highlighting each country's current emissions, post-2020 reduction targets, and adaptation priorities and are updated every five years. They provide decision-makers with a baseline framework to reference when designing mitigation or adaptation policy or projects. To date, 192 parties have submitted NDCs to the United Nations Framework on Climate Change (UNFCCC),[30] including 75 parties that have submitted updated NDCs as of December 31 2020.[31] The World Bank is the biggest funder for climate investments in developing countries, investing $83 billion over the last five years.[32]

NDCs and Agriculture

Agriculture is a key strategy for climate change mitigation and adaptation in NDCs, especially in developing countries.[23] It is among the most frequently included subsectors; 148 parties (of 161 total) that had submitted Intended NDCs (INDCs) in 2016 included agriculture in their mitigation targets, and 127 highlighted crops and livestock as an adaptation priority.[33] The most common agriculture mitigation measures mentioned include enteric fermentation management, animal management, reduced tillage, mulching, cover crops, crop residue management, rice management, agroforestry, and grassland and manure management.[23] These could have important impacts on soils, as outlined above, and therefore require effective monitoring and reporting of soil carbon. The UNFCCC has also formally recognized the role of agriculture through the Koronivia Joint Work on Agriculture (decision 4/CP.23). Ten countries explicitly referred to soil carbon in their INDC agricultural mitigation targets, while five others referred to soil carbon without setting direct targets. Ensuring project-level reporting of soil carbon in the agricultural sector (outside of carbon market projects) is in line with national emissions reporting is vital as NDC targets begin to drive climate action and funding priorities across sectors and countries. In Annex I countries, national reporting is driven by annual National Inventory Reports submitted to the UNFCCC, which must include a chapter accounting for emissions from agriculture.[34] Non-Annex II countries instead submit National Communications to the UNFCCC every four years, which report national GHG inventories, including emissions from agriculture.[35]

Chapter 2 of this Sourcebook provides guidance to projects seeking to design soil organic carbon assessment and monitoring approaches aligned with the requirements of assessing carbon finance and meet NDC reporting requirements.

CHAPTER 2: DESIGN OF A SOIL CARBON ASSESSMENT APPROACH

This chapter provides guidance on how to design a soil carbon assessment and monitoring system, and how to leverage methodologies to meet project needs.

CHOOSING A SOIL CARBON ASSESSMENT AND MONITORING SYSTEM

This Chapter aims to assist practitioners in making decisions regarding the best soil carbon assessment and monitoring approach. The Chapter starts with guidance on how to choose an approach for soil carbon assessment, followed by guidance on how to choose a methodology and how to integrate an assessment within existing MRV systems. The Chapter further describes how aligning monitoring at the project scale with landscape, jurisdictional, and/or national commitments has the potential to increase MRV cost-effectiveness, improve data collection and thus the robustness of the estimates generated, and increase access to finance. Additional considerations in developing a carbon assessment approach are provided in a Frequently Asked Questions (FAQ) format at the end of the module.

Choosing a soil carbon assessment approach depends on a) the purpose of the assessment, b) resources available for investment in monitoring, and c) the likelihood that the purpose of the assessment will evolve in the future.

We divide the purpose of a soil carbon assessment into four groupings, based on the required level of accuracy assessing soil organic carbon:

1. Reporting to a donor, such as project impact reporting to the World Bank (see an example in Box 2.1);
2. Reporting to a commodity buyer, such a contributing to a company's climate targets;
3. Access to environmental finance, such as payment per performance, payment for ecosystem services; and
4. Access to the voluntary carbon market through the production of carbon credits.

Reporting to national commitments, for example NDCs, would follow the framework of simplified reporting without seeking high-end carbon monitoring for financing like voluntary carbon markets would require – although typically would require direct adoption of the approaches used in the national inventory. Accessing the global carbon market requires more detailed reporting, verification, and validation, while reporting to a donor, commodity buyer, or national commitments and pledges may require only an estimate of soil carbon gains or tracking of soil carbon changes over time. Depending on the project purpose, different monitoring approaches are more relevant (Figure 12), going from basic (i.e., reporting to a donor) to high-end (i.e., carbon certification) performance-based carbon assessment and monitoring (Table 3).

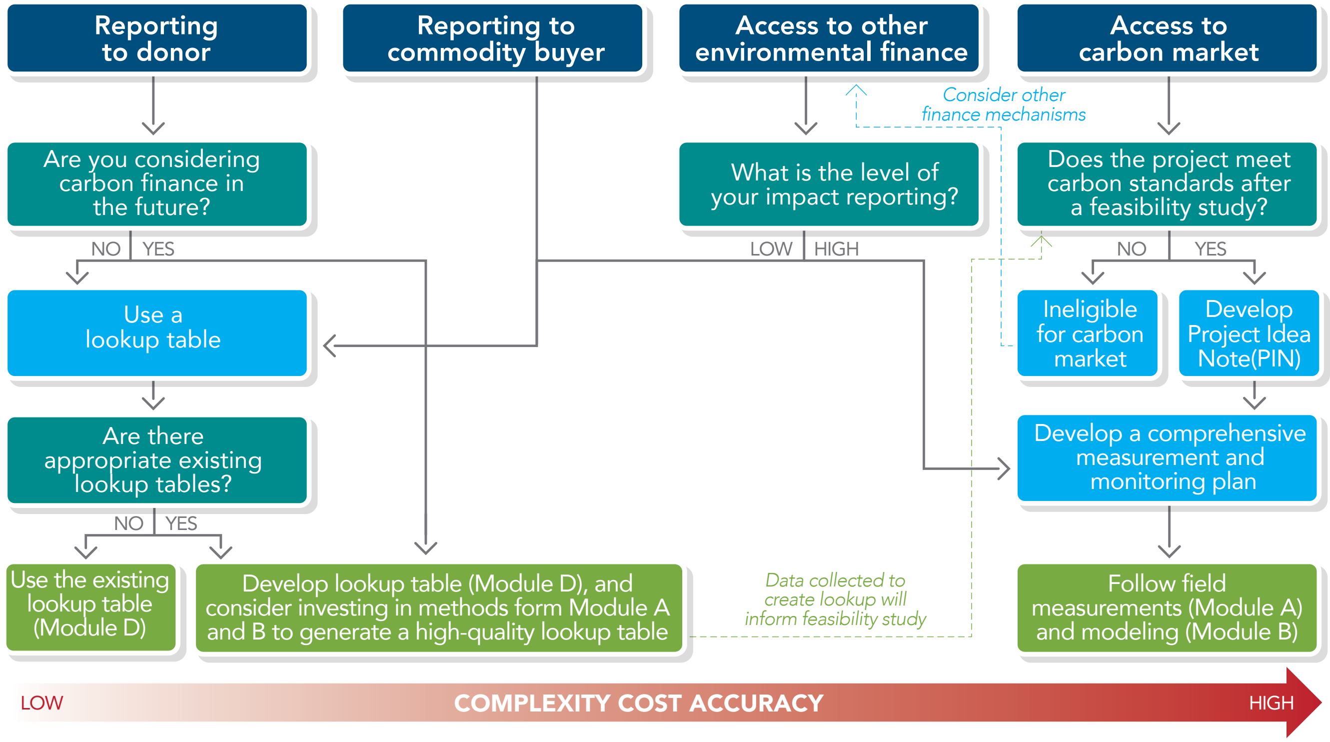


Figure 12. Decision-making tree for choosing a soil carbon assessment approach.

BOX 2.1 WORLD BANK METHODOLOGICAL REQUIREMENTS FOR CARBON FINANCING OF PROJECTS IN AGRICULTURAL SETTINGS

The World Bank's Sustainable Land Management Portfolio primarily uses the Ex-Ante Appraisal Carbon-Balance Tool (EX-ACT), developed by FAO following IPCC Guidance, to assess potential GHG and carbon sequestration impact of development projects in the agriculture, forestry, and other land use (AFOLU) sector. Learning resources for EX-ACT can be found at the **World Bank Open Learning Campus website**. Furthermore, the World Bank's Biocarbon Fund has developed the Sustainable Agricultural Land Management Methodology (SALM) to provide small-scale farmers in developing countries with protocols to quantify carbon emissions and removals. SALM is one of the approved VCS methodologies.[114]

Despite the different levels of accuracy of these options and thus the uncertainty associated with the soil carbon estimates they generate, all data, methods, and calculations need to meet the required level of quality and detail laid out by the carbon finance or reporting framework followed, and in any case must align at minimum with basic requirements set forth by the IPCC Guidelines[36] on general guidance and reporting of GHG inventories, adopted by NDCs and Biennial update Reports (BURs) to the UNFCCC.

Table 3. Soil carbon MRV categories with requirements and options for improvement

SOC MRV categories	Purpose	Technical requirements	Personnel requirements	Quick options for improvement of assessments
Basic	Public communication and donor reporting	Typical M&E systems, mostly based on periodic reporting of per area or per head management practices without intensive data collection	Closely linked to the existing advisory and extension system	GIS based activity data using global available land use datasets and lookup tables
Intermediate	Results-based payments	Occasional field surveys using digital data collection and central databases	Surveys done by enumerators, verified by field extension staff	Data collection toolkits, lookup tables, calculators or simple carbon models, development of Standard Operating Procedures for field data collection and development of sampling and monitoring plan
High-end	Carbon credit generation, high-impact carbon finance	Combination of digital field data collection and central Management Information Systems to automatize analyses and reporting	MRV staff with clear roles and responsibilities, central MRV unit, involvement of beneficiaries in monitoring	Standard Operating Procedures and QA/QC steps for all activities related to MRV, provision of continuous training and database maintenance

Case Study 1.7: Eco-schemes as a payment for practice model in the European Union

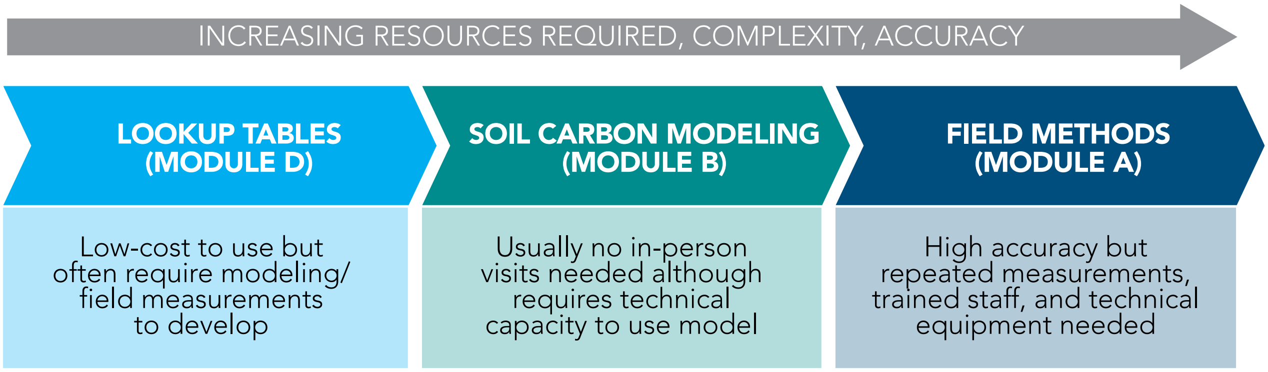
Eco-schemes are agricultural payment schemes incentivizing activities related to climate, environment, animal welfare, and antimicrobial resistance. They were introduced in the European Union in 2018 as part of the Common Agricultural Policy (CAP) and will contribute to achieving the EU's Green Deal Targets.[113] Funded by the EU, eco-schemes will provide annual payments to farmers implementing agroecology, agroforestry, organic farming, carbon agriculture, improved nutrient management, and other environmentally beneficial practices. Payments are provided in two ways that can be considered as payment-for-practice, depending on local managing authorities: either a) basic income support based on the actual or expected results to be achieved or b) covering costs incurred and income foregone as a result of implementing practices.[113]

CHOOSING A SOIL CARBON ASSESSMENT METHOD

As shown in Figure 12, depending on the level of complexity, accuracy, and costs, the project will have three broad carbon assessment methods to use. These can be implemented as standalone approaches or combined to meet project needs and carbon monitoring requirements cost-effectively over time. Depending on these needs and requirements, a combination of non-field and field methods will be required, for example to calibrate carbon models and validate the estimates (see Module B for in-depth guidance on this). Similarly, the lookup tables method (Module D) would rely on data generated through modeling, field measurements, technology, and literature or database review to develop new lookup tables useful for the project to assess soil carbon and monitor its potential changes over time (soil carbon MRV). Both modeling and field methods can be supported by technological approaches that can facilitate data collection on implemented practices (e.g., remote sensing) or carbon stocks (e.g., soil sensors). Module C explains in detail these technologies, including guidance on how to use them and their limitations. Furthermore, Annex I provides detailed information about how to select standard carbon methodologies and develop project baselines to monitor carbon benefits over time.

A summary of key benefits and drawbacks of the three approaches is presented in Figure 13, with each of them explored in more detail below. For a full description and guidance on how to implement these methods, we refer the reader to the specific modules – Module A for field methods, Module B for modeling, Module C for technological advances to support field and modeling assessments, and Module D for developing lookup tables.

Figure 13. Comparative complexity of soil carbon assessment approaches from Module A, B, D.



LOOKUP TABLES (MODULE D)	SOIL CARBON MODELING (MODULE B)	FIELD METHODS (MODULE A)
Low-cost to use but often require modeling/ field measurements to develop	Usually no in-person visits needed although requires technical capacity to use model	High accuracy but repeated measurements, trained staff, and technical equipment needed

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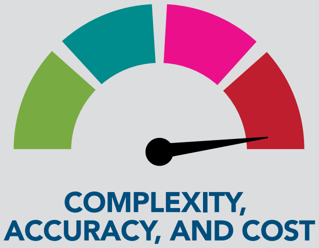
1. Field methods (Module A)



ADVANTAGES

- Most accurate and precise estimate of soil carbon impacts.
- Tailored data collection.

DISADVANTAGES

- Logistically challenging – requires repeat visits to multiple field locations.
- Expensive – requires equipment, staff, and laboratory analysis.

Key uses of field measurements include:

a) as part of a comprehensive monitoring plan used for reporting for participation in the global carbon market,
b) to parameterize and validate modeling, and
c) to take initial measurements for the development of lookup tables.

When implemented correctly, field measurements provide robust outcomes to establish a baseline and estimate potential gains.

Questions to ask in deciding whether field measurement is appropriate include:

- **Is field measurement required in the methodology prescribed by the carbon market, environmental market, or funding source?** If yes, follow those guidelines for collecting data. For many carbon standards, this would also require an estimate of uncertainty, which would require a statistical sampling-based approach described in more detail in Module A.
- **Do you have sufficient resources, time, and capacity to collect data?** If yes, ensure the project has trained staff to perform measurements, appropriate equipment as outlined in Module A, and access to laboratories to analyze samples collected in the field.
- **Do you have access to take field measurements from the site on a regular basis?** When set up for monitoring over a longer time period, a thorough plan for how repeated measurements should be taken to ensure comparability over time is required, following the recommendations laid out in Module A. If there is no access to take repeated measurements, ongoing field measurement should not be the primary monitoring method.
- **What are the alternatives to direct soil carbon measurement in the field?** When estimating changes in soil carbon stocks is not cost-effective and statistically inefficient, traditional statistical approaches (i.e. design-based inference) can be replaced by methods based on model-based inference or geostatistics, which provide spatial explicit estimates with less field sampling.

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2. Soil carbon modeling (Module B – Process-based modeling)

COMPLEXITY, ACCURACY, AND COST

ADVANTAGES

- Cost-effective to scale to large areas.
- Does not require visiting sites repeatedly or use of laboratory facilities.
- Allows correction for outliers from input data.

DISADVANTAGES

- Requires software.
- Requires high level of expertise and experience with the model.
- Limited by existing parameterization and components of model.

Key uses of soil carbon modeling include:

a) monitoring for carbon market finance, when the carbon standard explicitly requires the use of a specific model,
b) monitoring for donor reporting, and
c) developing lookup table values.

Soil carbon models can provide sufficient outcomes to establish a baseline and estimate potential gains. They are very useful for longer-term predictions of future trends for which data is currently not available. They are also lower cost, require less equipment, and involve fewer logistics than field measurement, although measurements during the initial assessment and/or during implementation for validation may be required for the model (see Module B for a breakdown of requirements by model). Modeling outputs and inputs vary based on the selected model and therefore careful consideration needs to be made when choosing a model.

Process-based models are especially useful when compared to empirical models, as they simulate the dynamic processes that influence soil carbon levels. Process-based models allow land use management history to be considered and permit the use of site-specific data to produce accurate results with lower uncertainty than empirical models.

Questions to ask in this decision process could include:

- **What model should I use?** Refer to Module B for more detail on how to choose an appropriate carbon model. If the carbon market standard explicitly requires one type of model, this model should be used. For many carbon standards, this would also require an estimate of uncertainty, which should be produced based on model guidelines.

- **What inputs are available?** If there is no specified carbon market requirement or the model is being used just for reporting purposes, compare what inputs each model requires to what is readily available at the project site and select the model with the most relevant inputs (e.g., if the project focuses on a change in crop residue management practices, select a model in which plant inputs are considered).
- **How much expertise does the model require?** There is a different learning curve for different models. If the model is highly complex, it may be necessary to hire an expert or consultant to run the model for the project.
- **What soil types is the model relevant to?** If the model is most relevant to a particular soil type or region, select the model that is most appropriate for your project area.
- **Is hiring a consultant to do the modeling going to be necessary?** If yes, the scope of work, timeline, and data needs will need to be defined to ensure efficiency in the contracted work.

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3. Lookup tables (Module D)


COMPLEXITY, ACCURACY, AND COST

ADVANTAGES	DISADVANTAGES
• Cost-effective. • Allows for long term monitoring and easy expansion of project area. • Typically requires reporting just the area under a given management practice.	• Can be challenging to develop based on data availability or need for model expertise.

Key uses of look up table approaches include:

a) when long-term monitoring is needed for a project in which the area of intervention is expected to change over time,
b) when financial constraints or capacity render modeling or field measurements not possible but knowing potential carbon benefits of land management activities and their associated uncertainty is necessary,
c) when detailed reporting is not required (i.e., not used for carbon market reporting) but an estimate of potential carbon gains is necessary,
d) when a simple or preliminary *ex ante* estimation of potential benefits is needed to prioritize action, and
e) when currently available IPCC default factors are outdated, too coarse for the purpose of the assessment, or not applicable to the type of activities being implemented and/or monitored by the project.

Lookup tables, despite being used often by national agencies and being able to be updated frequently with new data, are not as relevant as field measurement or modeling would be for projects hoping to access financing through the carbon market. Although developing a lookup table may initially be resource-intensive, it requires almost no effort to use once it has been created for a region and therefore offers an opportunity for consistent long-term monitoring.

Important questions when deciding to use a lookup table include:

- **Does the accuracy of a lookup table meet the reporting needs for the project?** If no, field measurement (Module A) or modeling (Module B) will need to be used.
- **Does a lookup table relevant to the project region and management practice already exist?** If yes, this should be used after ensuring it is of high data quality and is appropriate.
- **Does the project involve land in different agricultural management practices/regions/climates for which a lookup table would facilitate long-term monitoring?** If yes and if no lookup table exists, it is likely appropriate to develop a lookup table using the steps outlined in Module D, which could be used throughout the length of the project over the entire project area to ensure consistency and comparability.

INTEGRATING SOIL CARBON ASSESSMENTS IN MRV SYSTEMS

A soil carbon MRV system should be guided by the purpose for soil monitoring and the available resources to establish it. A list of existing soil MRV guidance frameworks, initiatives, and protocols is available in Annex III. These resources help build technical capacity on setting soil organic carbon MRV systems and for improving the accuracy of soil carbon accounting using field sampling and modeling approaches. Assessing soil organic carbon over time (i.e., monitoring) is useful not only to track changes in carbon stocks due to changes in land management practices. Long-term studies and monitoring are also useful to understand long-term dynamics of soil organic carbon that can help determine the sustainability of specific management approaches.

Soil carbon accounting and monitoring are typically designed as a practice-based (or activity-based) assessment, i.e. based on collecting and reporting information on project activities. Activities can be tracked through surveys and statistics or remote sensing (Module C). Soil carbon stock and stock change values are often modeled (Module B) to assess activities' soil organic carbon impact over time. To accurately assess this carbon impact, models (and especially process-based models) must be previously validated for the target region (most often with field measurement - Module A) to verify assessments and adjust models as needed.

The accuracy of determining soil organic carbon changes using practice-based and modelling approaches depends on the quality of the data inputs. While soil carbon models and practice-based monitoring can reduce the cost and complexity of soil carbon MRV significantly, the estimates they generate can have higher uncertainty compared to field-based approaches.

In this context, the use of lookup tables (Module D) has been particularly successful for soil carbon MRV at scale. Numerous MRV systems around the world (e.g., Alberta Carbon Offset System, the California Department of Food and Agriculture Office of Environmental Farming and Innovation (CDFA), or the California Air Resources Board, to name a few) use a model calibrated and validated with soil organic carbon field measurements to generate lookup tables of net GHG emission reductions from the implementation of eligible practices for the different climate and soil conditions of the region. These lookup tables are then used in project MRV.

Nationally Determined Contributions are an example of program that uses an MRV system. Projects looking to integrate with an NDC will typically have to adopt the activity data and fixed emission or sequestration factors used in the NDC's MRV system. Maintaining a good relationship with key officials and stakeholders at the national government can be a valuable asset for both the project and the government, as project data can be used to enhance an existing MRV system (e.g., National GHG Inventories or national AFOLU statistics) as the project develops and evolves, and project activity data that builds on existing national statistical systems can potentially increase its robustness and cost-effectiveness (see Box 2.2).

Recommendations:

In addition to the recommendations to assess soil organic carbon and soil organic carbon changes provided throughout Chapter 3, a reliable and cost-effective soil carbon MRV system should be:

- Based on existing institutional monitoring structures that provide accountability and, if possible, using parameters already being regularly monitored.
- Supported by decision-making bodies composed of policymakers, academia, project implementers, farmers, and any other relevant stakeholders.
- Aligned farmers' or stakeholders' interest through bottom-up activity-based approaches and incentive structures, engaging them in the design and implementation of the proposed data system.
- Designed with an activity-based MRV approach that achieves multiple benefits, if possible.
- Engaging farmers in a way that maintains transparency and builds capacity to facilitate sustainable long-term implementation.
- Aligned with QA/QC provisions to ensure assessments meet the highest standards of quality and reliability, regardless of the complexity and accuracy level. Uncertainties and biases of all MRV components must be identified and reported, for transparency.
- Designed to leverage existing datasets in combination with field assessments and modeling.
- Designed to adopt model-informed lookup tables for reducing costs and complexity of soil organic carbon accounting and monitoring.
- Intended to build datasets for filling data gaps (e.g., field surveys and climate stations).

BOX 2.2 DEVELOPING A CARBON ASSESSMENT AND MONITORING APPROACH THAT INFORMS NATIONAL, REGIONAL, OR JURISDICTIONAL STRATEGIES AND COMMITMENTS

Projects promoting the adoption of sustainable agricultural practices that conserve, increase, and restore soil organic carbon have the potential to be integrated into larger strategies to reduce emissions from agricultural settings, such as NDC commitments. The process requires a thorough assessment of any existing MRV structures in the agriculture sector in order to determine how to best align soil carbon monitoring approaches. This includes an understanding of:

- institutional and regulatory environment,
- available structures and arrangements for collection of farm-based data,
- type of data already being collected,
- frequency of data collection and reporting, and
- existing data gaps.

Where NDC or similar commitments exist, alignment is possible as long as soil organic carbon measuring and monitoring approaches are aligned and compatible with existing monitoring structures. In practice this means that the level of accuracy of the estimates pursued by the project would need to be similar or higher than the existing MRV system in place.

Where NDC-like commitments to reduce emissions from agriculture do not exist, projects should engage with government representatives or focal points responsible for GHG monitoring and reporting (e.g., offices in a Ministry of Environment of Environmental Agency, Ministry or Department of Agriculture, or other), and propose pathways for scaling project soil organic carbon MRV approaches to a national or jurisdictional level.

Projects investing in agricultural practices can link their progress to NDC commitments and expand their access to additional funding sources, either within the World Bank thought its NDC-SF or through other grants, in addition to the carbon finance pathways outlined on Figure 12. Furthermore, linking a project MRV system to an existing national Monitoring and Evaluation (M&E) institutional structure can increase project cost-effectiveness, if parameters already being monitored regularly as part of any existing system can be integrated into the project monitoring system, or if government databases and default factors become available to the project.

ADDITIONAL CONSIDERATIONS IN DEVELOPING A CARBON ASSESSMENT METHOD

Some common questions which arise in carbon assessment are included below.

1. Should carbon sequestration in the absence of the project (the baseline) be considered?

There are circumstances where the carbon stocks in the absence of the project are not stable. This can occur if there has been a recent change in land use such as conversion from forest to agriculture, in which case the soil stocks are decreasing, or a change in management, for example, recent adoption of application of manure where soil carbon stocks will be increasing. The carbon stock in the absence of the project is termed the *baseline*. Where carbon stocks are decreasing or stable it is conservative to ignore any baseline. This will capture most cases for agricultural soils.

- A baseline will not usually need to be calculated in estimating the change in soil carbon for reporting to a donor or commodity buyer.
- If seeking carbon financing from a carbon market, any carbon sequestration in the absence of the project needs to be considered. Rather than just calculating the change in sequestration from adopted management practices, initial levels of soil carbon stocks, emissions, and sequestration will need to be accounted. The baseline will depend on current soil management practices and would represent a business-as-usual scenario. If activities at the baseline include soil carbon accumulation (e.g., planting trees, increasing manure application), the project will have to demonstrate an additional carbon sequestration due to project activities. The market will determine how the baseline must be considered. See Annex 1 for an overview of existing carbon markets, baselines, additionality, and the steps to develop a project eligible for carbon projects.

2. Should impacts of decreases in production or displacement of farmers be considered?

A displacement of farmers or production from the project area to another region could negate any carbon sequestration occurring within the project boundaries (known as *leakage*).

- If seeking financing from the carbon market, the project will need to demonstrate that there is no leakage occurring because of the project. In any circumstance, it is good practice to ensure there is no displacement of people or a decrease in production and if there is, that there be plans in place to mitigate any displacement. See Annex 1 for a description of leakage and how it is addressed in different carbon standards.

3. Should carbon intensity be considered?

Carbon intensity reflects the greenhouse gas emissions or sequestration per unit of production. Intensity can be more important than total emissions as an indicator of success in farm management, as it captures any changes in production related to a change in sequestration or emissions. Calculating intensity as an indicator of soil carbon management would allow farmers to increase production (and potentially total overall emissions) without it being reflected as a negative in terms of emissions.

- Carbon intensity is likely an important metric where reporting occurs to international commodity buyers.

4. How large does the intervention area need to be?

- The size of a program may impact its eligibility in a carbon market. Refer to Annex I for more detail on carbon markets eligibility.
- Reporting to donors, community buyers, or other environmental finance options would not be likely to limit eligibility to a certain intervention area size, but conditions might vary on a case by case basis.

5. Does the impact of fossil fuels and fertilizers need to be tracked?

- If the goal of the assessment is to reduce the carbon footprint of agricultural (i.e., cropland or grazing land) management, yes it needs to be tracked. However, this kind of comprehensive net carbon assessment might only be relevant in the carbon market scenario, unless donors, commodity buyers, or environmental finance bodies explicitly request measurement and monitoring of fossil fuel use and fertilizer emissions.
- This Sourcebook focuses on soil carbon and thus does not provide guidance on how to measure, monitor, and report emissions from soil fertilizers or fossil fuel use in agricultural settings. Guidance on this matter can be found in the IPCC 2006 Guidelines[37] and in the methodologies approved by voluntary carbon market standards. National-level methodologies may also be available to estimate these emissions through the Ministry of Environment or other appropriate government branch, as may agricultural carbon calculators such as the US Cropland Greenhouse Gas Calculator,[38] Cool Farm Tool,[39] and EX-ACT tool,[40] which could be used if a specific methodology is not specified in reporting requirements.

6. When should a bottom-up approach to engage smallholder farmers in data collection be used?

- If there are farmers engaged in the program or project who can participate in data collection and monitoring, it may be worth engaging them to increase sample sizes, have more routine data collection, and contribute to project overall success. Local engagement after necessary training can increase data collection efficiency and facilitate field campaigns.
- Sufficient training will be a key requirement to ensure that data is accurate, comprehensive, and comparable. Farmer engagement also may be appropriate for some (e.g., manure and fertilizer application amounts, vegetation residues applied), but not all, measurements (e.g., samples that need to be sent to a laboratory).

7. How should projects deal with the risk of reversal or risks of non-permanence of carbon sequestered by the project?

- Reversing a soil management approach that increases soil organic carbon will lead to the loss of the carbon benefits generated with implementation. Because soil carbon benefits can take longer to be generated than they could take to be lost, it is key that project and land managers account for carbon benefits that are projected to be maintained over long periods of time (e.g., over 20 years, the time frame suggested by the IPCC to see changes in soil organic carbon stocks with land use management change[32]).
- There are tools available to assess potential risks of reversals that would lead to the non-permanence (i.e., loss) of the carbon benefits generated, such as the Non-Permanence Risk Tool from VCS.[41]

CHAPTER 3: ASSESSING SOIL CARBON STOCKS AND CARBON STOCK CHANGES

Building on Chapter 2, this chapter provides guidance on the three main processes and procedures for assessing soil carbon stock including the following modules:

- *Field measurement of soil carbon*
- *Soil carbon modeling approaches*
- *Technology options to supplement soil carbon data*
- *How to develop lookup tables for agricultural practices*

MODULE A: FIELD MEASUREMENT OF SOIL CARBON

The collection of soil samples from the field and subsequent analysis will always be the most accurate way of assessing soil carbon stocks and stock changes associated with agricultural management practices in croplands and grazing lands. Collecting and analyzing soil samples, however, is often *logistically challenging*, *time-consuming*, and *expensive*, particularly if it involves traveling to the field site and purchasing or renting basic field equipment. Collecting soil samples also requires a skilled field crew, as well as facilities to safely store and analyze the soil. Because sample analyses cannot usually be done on site, obtaining soil carbon estimates requires the transport of collected samples to laboratory facilities. Furthermore, laboratory costs for soil carbon assessment can range from low to high, with lower costs typically associated with lower accuracy.

Deciding the best approach for sampling and analysis must be tailored to the focus of the assessment, the required level of accuracy to meet assessment goals, and the resources available to perform the assessment. All these must be determined when designing the soil carbon measurement plan before going to the field. Having a cost and time efficient field sampling plan that is tailored to the scope and needs of the assessment is a fundamental component of soil carbon assessments based on field data collection.

To provide guidance in all these aspects of assessing soil carbon stocks, this Module is structured in three parts:

- ***Part A:*** Field methods to assess soil carbon
- ***Part B:*** Laboratory methods to assess soil carbon
- ***Part C:*** How to design a soil carbon measurement plan

PART A: FIELD METHODS TO ASSESS SOIL CARBON

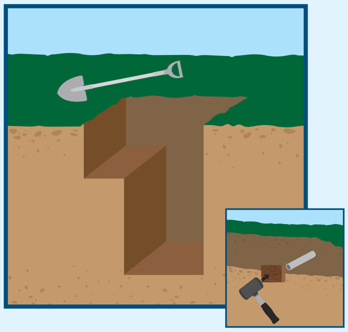
Soil sampling for direct measurement of soil carbon

1. Soil sampling methods

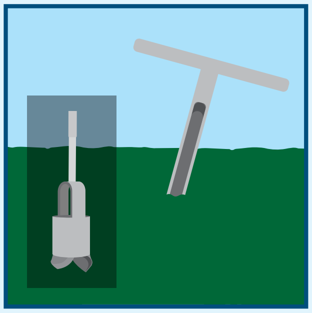
There are two methods to sample soil:[42] 1) digging open pits; and 2) taking soil cores. Box 3.1 provides a quick overview of these options; further details on how to collect and handle samples are provided below.

Table 4 lists recommended equipment to bring to the field and its purpose during soil sampling for carbon assessments.

BOX 3.1 SOIL SAMPLING METHODS



Open pits:
This is the only method to examine the soil column in natural conditions and requires excavating a pit large enough to fit field staff comfortably during sampling. It is time-consuming and might require excavating equipment. It is unlikely to be feasible in a productive agricultural site, given the significant disturbance to the site that this method entails. Soil sample units in a pit are taken horizontally with a coring or soil sampling device.



Coring:
An auger or soil probe is inserted vertically into the soil from the surface, minimizing disturbance of the field site. Each time a sample unit is retrieved, the auger can be re-inserted in the sampled hole to collect a deeper soil sample unit, while the soil probe collects a long soil core in one extraction, keeping the soil intact.

Table 4. Recommended field equipment for soil sample collection.

Equipment	Purpose
GPS, map	Record coring location
Field notes and datasheets	Quick guide and recording of relevant field data
Excavating equipment	Pit digging, if open pit method is followed
Coring or auger device	Soil sampling
Measuring tape	Assessment of soil core depth
Knife	Soil core subsampling into depth increments
Airtight plastic bags or tin containers, labeled	Pack and store samples until analyses
Cooler	Carry and preserve packed samples during field campaign

2. Sampling to measure soil carbon stocks

Soil carbon stock refers to the mass of carbon in soil per area to a given depth. An accurate assessment of soil carbon therefore requires measuring three soil parameters at each sampling site:

(1) Bulk density:

Bulk density changes with land use and management practice.

Soil bulk density refers to the amount of soil mass in a known, intact volume of soil. It varies with multiple natural and anthropogenic factors. Because soil organic matter is lighter than other mineral soil particles (sand, silt, or clay), the more organic the soil is, the lower its bulk density tends to be, i.e., there is less soil mass in a given volume if there is a lot of organic carbon in the soil. Similarly, practices that compact or disaggregate soil clusters would increase bulk density, whereas the surface soil bulk density will be lower immediately after practices that disturb and aerate the soil (e.g., tillage) than at the end of the growing season.

When taking soil cores to determine bulk density it is most important to collect a core as intact as possible, so it represents field volume occupied by soil solids and pore space.

Recommendations:

- Gouge augers can vary in length and diameter; while longer ones might be more difficult to handle, it is recommended to use one long enough to reach the desired soil depth in one insertion, although neatly extracted cores will allow reinsertion of the device to extract a deeper soil sample unit.
- Beware of soil compaction. If fully inserting a probe into the soil results in an incomplete core, it is likely compaction has occurred and the bulk density will be incorrect. This sample unit must be repeated.
- It is good practice to measure the depth of the core extracted and compare it to the depth reached by the corer, to assess compaction and retake the core if needed.

(2) Carbon content:

Carbon content is the proportion of soil mass that is carbon (rather than other constituents such as silicon), and it can be in an organic or inorganic form. Carbon content is usually expressed as a percentage (%) or mass of soil carbon over the mass of soil (e.g., g C kg^{-1} soil). Because soil organic carbon content is influenced by soil management and natural impacts (e.g., wind or water erosion or localized decomposition), it can vary within meters of distance or less, thus it is good practice to take multiple cores for carbon content at each sampling site and pack them as independent sample units or mix them to create a "composite" sample to reduce inter-sampling variability. Typically, separate cores are collected for carbon content and bulk density; composite sampling is not appropriate for samples to be used for soil bulk density determination unless volumes are accurately recorded and no soil is lost in the pooling process.

Recommendation:

- Samples taken for soil carbon determination should avoid any contamination with grease or other organic materials that would alter the carbon estimate during analysis.

(3) Depth:

The greatest soil organic carbon change in most agricultural systems is observed in the top 30 cm, although depending on management practices (e.g., deep plow) it might be necessary to assess soil organic carbon changes at a greater depth. A 50 cm depth would be recommended in circumstances with deep soil disturbance.[2]or 25 to 40 Mg C/ha, upon conversion from natural to agricultural ecosystems. About 60 to 70% of the C thus depleted can be resequestered through adoption of recommended soil and crop management practices. These practices include conversion from plow till to no till, frequent use of winter cover crops in the rotation cycle, elimination of summer fallow, integrated nutrient management along with liberal use of biosolids and biological nitrogen fixation, precision farming to minimize losses and enhance fertilizer use efficiency, and use of improved varieties with ability to produce large root biomass with high content of lignin and suberin. The gross rate of soil organic carbon (SOC Because carbon differences at greater depths are beyond the typical crop or grass influence depth and thus not a consequence of project implementation, collecting deeper cores is not necessary to assess carbon impact of agricultural practices. Cores are often taken down to 1 m or down to the parent material in other settings to get a complete assessment of the soil profile, yet this would not be a relevant measurement in the context of this Sourcebook.

Depth increments within the core (e.g., every 5 or 10 cm) can be measured and recorded before the soil is extracted from the coring device (see Box 3.2). Sectioning the soil core by these depth increments will allow analyzing sections individually to capture soil variability across the soil profile. Most assessments looking to monitor the net impact of agricultural management practices on soil carbon, however, will not need to report changes in carbon content by depth increment but as a total change in the entire top 30-50 cm of soil.

Recommendations:

- Cores should be collected in most instances to 30 cm depth with no depth increments.

BOX 3.2 COLLECTING SOIL SAMPLES

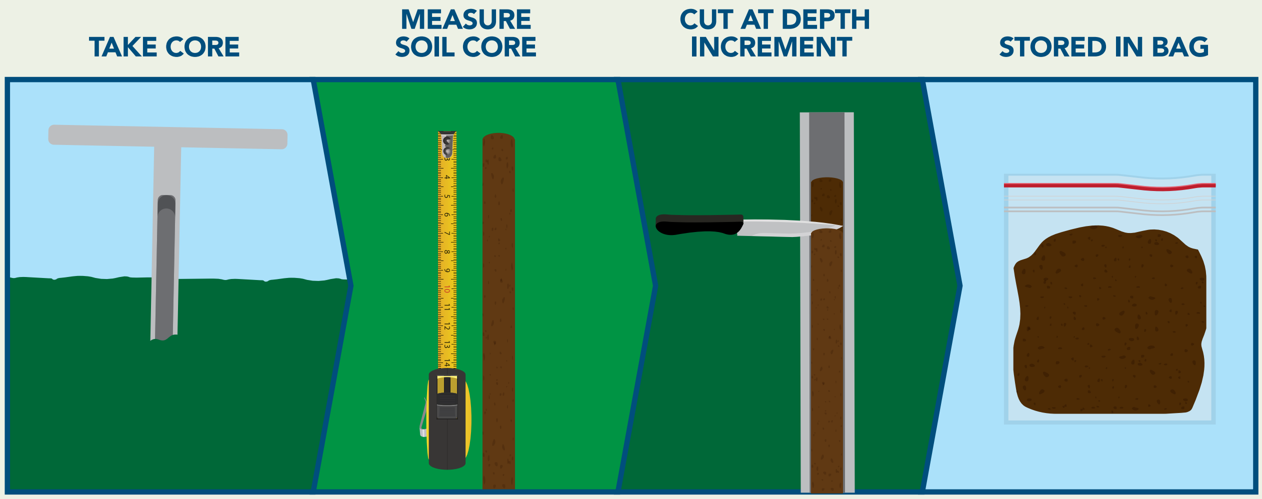
STEP 1: At the sampling sites where soil cores are going to be extracted, any plant debris, crop or litter residue, or manure must be removed from the soil surface before inserting the coring device (if the cores are taken from an open pit, the exposed side of the soil profile needs to be cleaned before inserting the coring device).

STEP 2: Insert the coring device into the ground perpendicular to the soil and retrieve it carefully in a similar motion, i.e., vertically from the soil surface (or parallel to the soil surface if cores are taken from an open pit).

STEP 3: Where differentiation of carbon stocks across depth is needed, extracted vertical soil cores need to be divided into depth increments without disturbing their integrity, while open pit cores are taken directly horizontally from the depth of interest. To divide vertical soil cores into depth increments, cut the soil sections perpendicular to the core with a sharp knife.

If cores are taken for soil analyses other than bulk density, they can be subsampled. Subsampling a core would be reasonable in circumstances of limited packing materials, cold storage space, or to save on transport costs. To collect a subsample at the depth of interest, soil would be taken at the mid-point of each depth increment of the core, and the rest of the soil in the core would be discarded. When subsampling, however, it is critical to know the minimum sample size for laboratory analysis.

STEP 4: Pack all soil sample units into separate airtight containers and label them carefully. Plastic bags are preferred packing containers to retain soil moisture. Labels should represent sampling site and date, sample type (bulk density or carbon content), core number, depth increment, and other key identification.



Calculations

Understanding the impact of a land management practice on soil's ability to store carbon requires estimating soil carbon stocks (t C ha^{-1}) in the site of interest. The soil carbon stock to a certain depth is a standardized metric comparable across sites, time steps, and carbon pools. The steps to calculate soil carbon stocks change are:

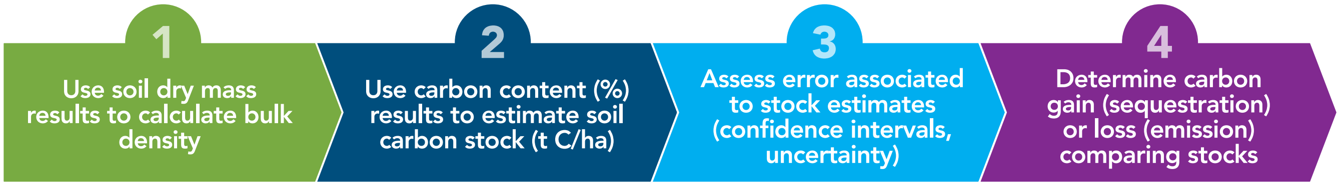


Figure 14. Flow of steps to calculate change in soil carbon stocks

Step 1: Calculate soil bulk density

Soil bulk density (D_b) is the soil mass (M_s) per unit of total volume (V_t):

$$\text{Eq. 1} \qquad D_b = \frac{M_s}{V_t}$$

M_s refers to dried soil mass and V_t to the volume of solids and pore space. D_b is reported as Mg m^{-3} or g cm^{-3}. Note that the sample unit volume represents the volume of the sample unit at the time of the original collection.

Coarse roots and mineral fragments (i.e. greater than 2 mm size) should be removed.[43] Soils with gravel and stones within the core would need a D_b corrected for the gravel and stone fraction[44]:

$$\text{Eq. 2} \qquad D_b = \frac{M_s}{(V_t\text{-}[RF/PD])}$$

Where *RF* is the mass of coarse fragments and *PD* the density of rock fragments (a default of 2.65 g cm^{-3} can be assumed).

EXAMPLE CALCULATIONS: BULK DENSITY

1. A soil core collected using a cylindrical 10 cm diameter probe generated the following hypothetical dry mass data:

Depth (cm)	Soil dry mass (g)
0-10	816.8
10-20	918.9
20-30	1,021.0

   The volume of a 10 cm long core increment would therefore be 785.4 cm3. Applying equation 1, the bulk density of the first depth increment would be:

$$D_{b1} = 816.8\ g/785.4\ cm^3 = 1.04\ g/cm^3$$

Depth (cm)	Bulk density (g/cm^3)
0-10	1.04
10-20	1.17
20-30	1.30

2. The soil was found to have rock fragments, weighing 100 g in the 10-20 cm depth increment and 50 g in the 20-30 cm one. Assuming a default rock fragment density of 2.65 g/cm3 and applying equation 2, the bulk density of the second depth increment would be:

$$D_{b1} = 919.9\ g/(785.4\ cm^3\text{-}[100/2.65]) = 1.23\ g/cm^3$$

Depth (cm)	Total soil dry mass (g)	Mass of rock fragments (g)	Bulk density (g/cm^3)
0-10	816.8	0	1.04
10-20	918.9	100.0	1.23
20-30	1,021.0	50.0	1.33

Step 2: Calculate soil carbon stock

1 Use soil dry mass results to calculate bulk density
2 Use carbon content (%) results to estimate soil carbon stock (t C/ha)
3 Assess error associated to stock estimates (confidence intervals, uncertainty)
4 Determine carbon gain (sequestration) or loss (emission) comparing stocks

Soil carbon stocks are typically calculated at fixed depths. To do so, use the laboratory results on soil carbon content (%), the calculated bulk density, and measured soil depth of the extracted core as:

Eq. 3
$$\text{Soil C Stock (t ha}^{-1}) = 100 * [\text{bulk density (g soil cm}^{-3}) * \text{soil depth (cm)} * \text{carbon concentration (\%/100)}]$$

Soils with the same carbon concentration but higher bulk density would therefore have higher carbon stocks. Alternatively, soil carbon stocks can be calculated as a function of "equivalent soil mass" (ESM), yet ESM is not consistently used and is not a standardized soil assessment methodology.

EXAMPLE CALCULATIONS: SOIL CARBON STOCKS

The lab analyses on a soil core collected in an agricultural field provided the following hypothetical data:

Depth (cm)	Soil carbon content (%)	Bulk density (g/cm^3)
0-10	2.0	1.04
10-20	1.74	1.23
20-30	1.43	1.33

Applying equation 3, soil carbon stocks for the first depth increment would be calculated as:

$$\text{Soil C stock}_1 = 100 \text{ x } [1.04 \text{ g/cm}^{-3} \text{ x } 10 \text{ cm x } (2\%/100)] = 20.8 \text{ t C/ha}$$

Depth (cm)	Soil carbon content (%)	Bulk density (g/cm^3)	Soil C stock (t C/ha)
0-10	2.0	1.04	20.8
10-20	1.74	1.23	21.4
20-30	1.43	1.33	19.0

The project wants to report top 30 cm stocks which, on average, are 20.4 t C/ha.

Step 3: Reporting results and their uncertainty

1 Use soil dry mass results to calculate bulk density
2 Use carbon content (%) results to estimate soil carbon stock (t C/ha)
3 Assess error associated to stock estimates (confidence intervals, uncertainty)
4 Determine carbon gain (sequestration) or loss (emission) comparing stocks

Once the outputs of the analysis have been reviewed and validated, actual results can be calculated. While it is good practice to keep records of raw data, it is not efficient to report raw data. Means or medians of the results generated for each field and analytical replicate will need to be calculated. Results should also be reported with a range or an associated uncertainty value, as means or medians are only an estimate of the true value of the carbon content. The total uncertainty or error associated with the result will therefore be a consequence of the sampling and the analysis errors. When standard methods and protocols are properly followed, it can be assumed that the error will be due to the actual variability of the carbon content in the soil analyzed, representative of the variability in the field. The resulting error range is generally expressed as the mean ($\bar{x}$) plus or minus half the confidence interval (± CI). Formulas to calculate these statistical measures and uncertainty through simple error propagation are provided in Box 3.3. Note that uncertainty requirements may vary based on the verification steps of a specific carbon market or project funder (see Annex I for more details or carbon market requirements).

Step 4: Determine carbon gains (sequestration) or losses (emissions)

1 Use soil dry mass results to calculate bulk density

2 Use carbon content (%) results to estimate soil carbon stock (t C/ha)

3 Assess error associated to stock estimates (confidence intervals, uncertainty)

4 Determine carbon gain (sequestration) or loss (emission) comparing stocks

Measuring carbon stock change in agricultural settings therefore entails resampling soils over time to determine carbon (C) stock gains and losses through a stock change approach:[45]

Eq. 4

$$\text{C Stock Change } (\text{t C ha}^{-1}) = \text{C stock time 2 } (\text{t C ha}^{-1}) - \text{C stock time 1 } (\text{t C ha}^{-1})$$

The rate of change is determined by dividing the stock change by the number of years between carbon stock determination and reported as t C $\text{ha}^{-1}\text{y}^{-1}$. It is good practice to do this as part of a Monte Carlo simulation, incorporating the uncertainty in the two measurements (see approaches to calculate and report uncertainty in Box 3.3).

Agricultural practices change soil carbon content by increasing carbon inputs or decreasing carbon outputs, rather than by changing soil accumulation. Estimating soil gain over time is therefore not necessary. However, practices expected to increase sediment accumulation will need to measure sedimentation rates to determine soil gains. Examples of field techniques to measure sedimentation are marker horizons (e.g., feldspar markers) and soil dating techniques (e.g., isotopic decay).

BOX 3.3 STATISTICAL MEASURES AND UNCERTAINTY ASSESSMENT

1. The arithmetic mean (**mean**) is the average value of the replicated samples (i.e., sample units).

   Eq. 5 $$\bar{x} = \frac{1}{n}\sum_{i=1}^{i=n} x_i$$

   Where $\bar{x}$ is the mean, x is the sampled value, and n is number of sample units.
2. The **standard deviation** provides a measurement of variation from the average value:

   Eq. 6 $$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{i=n}(x_i - \bar{x})^2}$$

   Where S is the sample standard deviation, x is the sampled unit value, n is the number of sample units, and $\bar{x}$ is the arithmetic mean. This equation is applicable to simple random sampling.
3. The **standard error** provides the standard deviation of the mean.

   Eq. 7 $$SE_{\bar{x}} = \frac{s}{\sqrt{n}}$$

   Where SE is the standard error, $\bar{x}$ is the arithmetic mean, s is the sample standard deviation, and n is the number of sample units. This equation is applicable to simple random sampling.
4. The **confidence interval** gives the estimated range of values likely to include an unknown population parameter at the chosen confidence level.

   Eq. 8 $$CI = t * SE_{\bar{x}}$$

   Where CI is the half width of the confidence interval at a specific confidence level or absolute error, often 95% or 90%, t is the t-value, function of the confidence level and the number of sample units, SE is the standard error, and $\bar{x}$ is the mean.
5. **Uncertainty** or relative margin of error is estimated as a percentage, using the half width of the confidence interval as a percent of the mean.

   Eq. 9 $$Uncertainty = \frac{CI}{\bar{x}}$$

   Where CI is the half width of the confidence interval at a specific confidence level, and $\bar{x}$ is the mean.

   When combining the results of independent analyses to produce one estimate, e.g., analysis of bulk density and of carbon content to estimate soil carbon stock, as shown in equation 3 above, uncertainties of each analysis must be calculated and the combined effect of uncertainty (i.e., uncertainty or error propagation) estimated. The IPCC provides guidance to derive the uncertainty of the product of two estimates (equation 10) and the addition or subtraction (equation 11):

   Eq. 10 $$U_{total} = \sqrt{U_1^2 + U_2^2 + \cdots + U_n^2}$$

   Where U_{total} is the total percentage uncertainty in the product of the quantities, at the chosen CI, and U_n is the percentage uncertainty associated with each of the quantities.

   Eq. 11 $$U_{total} = \frac{\sqrt{(U_1 * x_1)^2 + (U_2 * x_2)^2 + \cdots + (U_n * x_n)^2}}{|x_1 + x_2 + \cdots + x_n|}$$

   Where U_{total} is the total percentage uncertainty in the product of the quantities, at the chosen CI, U_n is the percentage uncertainty associated with each of the quantities, and x_i is the uncertainty quantity (measured result).

   Note that propagation of uncertainties must consider correlation between factors, both spatially and over time. Correlation can be calculated following equation 12.

   Eq. 12 $$r_{xy} = \frac{\sum(x_i - \bar{x}) \times (y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \times \sum(y_i - \bar{y})^2}}$$

   Where r is the correlation coefficient (from -1 to +1), $\bar{x}$ is the arithmetic mean, and x_i is the value in a sample.

PART B: LABORATORY METHODS TO ASSESS SOIL CARBON

Finding facilities for soil analyses

A professional soil laboratory is needed for reliable analysis of soil carbon. Suitable laboratories could be commercial, academic, or research centers, although available laboratories performing soil analysis may vary by country and by region.

Recommendation:

- Search for a laboratory that follows accepted standard sampling and carbon analysis procedures.

Although not exhaustive lists, several resources can serve as starting points to find a soil laboratory:

- The Food and Agriculture Organization's Global Soil Laboratory Network (GLOSOLAN) has an interactive map of over 400 registered soil laboratories adhering to international standard operating procedures.46
- The ISO/IEC 17025 (General requirements for the competence of testing and calibration laboratories) accreditation is one of the most widely used international certifications to verify quality laboratories. It is recommended to look through a list of ISO/IEC 17025 certified laboratories in the relevant country or region.
- In some countries, the national ministry responsible for agriculture or environment may maintain a list of nationally credited soil laboratories.
- Universities and research centers may have appropriate analytical laboratory facilities. It is recommended to look into whether laboratories at known academic and research institutions in the project area accept soil samples.

Recommendation:

Once several relevant labs have been identified, they should be contacted to ask the following questions:

1. What methodology is used to estimate bulk density: does the laboratory use a dry oven at recommended temperatures (see next section)?
2. What methodology is used to prepare soil carbon samples: does the laboratory use a 2 mm sieve and thoroughly mix and homogenize the soil?
3. What methodology is used to determine soil carbon content: wet or dry combustion? What is the dry combustion equipment? It is recommended to use a carbon analyzer for the highest reliability of results.
4. What are the standard quality assurance and quality control measures used in the laboratory (described further below)? Does the laboratory run analytical replicates? Does the laboratory routinely use reference check samples?
5. What is the standard price to analyze soil samples?
6. What is the standard time required to process samples?
7. Can the laboratory share the raw data and the quality assurance/quality control (QA/QC) records?

It is also important to consider the cost and time required to ship samples to the laboratory, as this may impact the storage used for fresh samples. Transporting samples to a laboratory internationally may involve additional regulations and complications (e.g., permits) and should be researched more closely on a case-by-case basis.

Selecting the appropriate laboratory analyses to assess soil carbon

Assessment of soil carbon stocks entails laboratory analysis of soil collected in the field for (1) bulk density and (2) carbon content.

Recommendation:

- It is best to proceed with laboratory analyses shortly after soils are collected, if possible. If samples need to be transported or shipped over large distances for analysis, they should be dried first.

(1) Bulk density:

Estimating bulk density requires measuring dry soil mass (M_s) and original volume sampled (V_t) of intact soil cores (or core subsection of known length). The dry mass is the air-dried or oven-dried weight of the soil. Using a drying oven is recommended for a minimum of 48 hours or until a constant weight is reached, at 105°C if the soil is mineral and 60°C if the soil is organic.[47]

(2) Carbon content:

Carbon content should be determined in a professional soil lab. There are several methods to determine soil carbon content that differ in analytical accuracy and cost (Table 5). They all require preliminary treatment consisting of drying to constant weight, grinding, and homogenization (i.e., well-mixed). If the goal of the assessment includes knowing how much inorganic carbon the soil contains, pre-treating a subset of the sample units with a strong acid will be necessary. [48]

Table 5. Comparison of laboratory methods to determine soil carbon content ranked from low (+) to high (+++).

Methods		Description	Complexity	Accuracy	Analysis time	Costs
Dry combustion	*Loss on ignition (LOI)*	Soil oven at 450°C.	+	+ *(semi-quantitative)*	+++	+
	Elemental analyzer	Automated furnace (1,000°C).	++	+++ *(quantitative)*	+	+++
Wet combustion	*Chemical digestion (Walkley-Black)*	Heat with chemicals. Hazardous waste.	+	++; + if carbon content is high *(semi-quantitative)*	++	+

Recommendation:

- The dry combustion method using an elemental analyzer is the recommended method to estimate soil carbon content in all kinds of soils for its accuracy and efficiency. The loss on ignition approach should not be used unless absolutely necessary.

Quality assurance/quality control in sampling and analysis

The principles of data quality assurance/quality control (QA/QC) should be applied in all carbon stock assessment programs. This typically means:

- Demonstrating sufficient training of responsible staff;
- Preparing and using standard operating procedures for all measurement and analysis;
- Verification procedures for field data collection, sample unit labeling, lab analyses, and data entry.

It is recommended to have a QA/QC plan in the project documentation where the procedures for the consistent collection of field samples, laboratory procedures, verification of data entry and calculations, and storage of data are detailed and incorporated into the staff training process. The QA/QC plan will also allow identifying early in the field, lab, and data analysis steps if corrective action is needed before the work is finished.

There are different points in the assessment process to perform QA/QC checks:

FIELD DATA COLLECTION HOT CHECKS	Verify during sampling that appropriate procedures are being followed.
LABORATORY CONTROL CHECKS	Use of standards or blanks to identify analytical errors in samples of known content.
FIELD AND LABORATORY DATA SHEET CHECKS	Review of field data gathered for completeness and accuracy. Field data should be inspected before data entry and analysis begins
DATA ENTRY CHECKS	Review of data entry for completeness and accuracy, comparing it to the original field or lab data sheet

These QA/QC checks during sampling, laboratory analyses, data entry, and calculations are intended to (1) identify and issues that need corrective action early on, and (2) to estimate the error associated with the measurement and thus to the final results. The target accuracy and precision of the assessment will determine the level of error allowed in the assessment; the QA/QC process must ensure the error associated with the results is below said allowable level. Box 3.4 provides additional guidance on QA/QC during sampling, laboratory analyses, and data analysis. Further guidance on assessing the level of accuracy and precision of the soil carbon assessment is provided in Part C of this Module, *How to design a soil carbon measurement plan*.

BOX 3.4 QA/QC RECOMMENDATIONS

Sampling:

- Collect sufficient samples to attain a desired level of precision in the results (see Part C of this Module). For carbon content collect multiple (e.g., three) samples at each sample point to capture variability that exists over small distances.
- If unfamiliar with the sampling device, first practice away from the area where project samples will be collected.
- Follow guidelines on sample collection and handling, avoiding contamination or conditions that affect soil carbon content in collected soils.
- Verify the methods used by all field staff and retrain where errors are discovered.
- Take note of any field conditions, extraordinary circumstances, or deviations from sampling protocol that could potentially help better explain the results of the analysis.

Laboratory results:

- Maintain equipment in good working order and perform preventive maintenance.
- Samples should be run in analytical replicates (x3) to reduce error.
- Confirm detection limits of the analysis method selected, and dilute samples if needed.
- Run soil sample analyses with standards (i.e., samples of known carbon content) to identify analytical errors.
- Verify all data collected before data analysis and calculations, and repeat analyses if necessary, if possible.

Data analyses and calculations:

- Keep a copy of the raw data.
- Follow statistical measures to report means with an estimate of variability or confidence interval.
- Assess uncertainty of the estimates either through simple error propagation or through more complex uncertainty assessments (i.e., assess uncertainty of the estimates either through simple error propagation or through more complex uncertainty assessments such as a Monte Carlo analysis).

PART C: HOW TO DESIGN A SOIL CARBON MEASUREMENT PLAN

As a result of the logistics and costs of fieldwork, it is key to have a cost and time efficient field sampling plan that is tailored to the scope and needs of the assessment. In the design of a measurement plan, decisions must be made on the boundaries of the assessment, the number of sample units to collect, and where and when to collect them. The flow of steps to design the measurement plan (Figure 15) and recommendations for each are explained in detail in the section below. These steps are applicable to croplands and grazing lands across regions, locations, timelines, and scales.

Figure 15. Flow chart of the steps to produce soil carbon assessments.[49]

Step 1: Define assessment boundaries

Defining the boundaries of the project includes delimiting the following aspects:

- *Project location or geographical/physical boundaries:* The boundaries of the intervention where carbon measurements and modeling are going to be conducted must be defined and delineated.
- *Measurement boundaries:* Assessments in agricultural settings must determine the depth of soil carbon that will be impacted by the focal agricultural practices and thus which will be measured through time – in most circumstances, a 30 cm depth will suffice though where deeper soil disturbance occurs, 50 cm may be needed. The included pools and gases must also be considered and may include live biomass especially if trees are being planted, and nitrous oxide where synthetic fertilizers are applied. However, the focus of this Sourcebook is just on soil carbon.

Recommendation:

- Once defined, boundaries should not be changed during the assessment period. All changes, however, will need to be properly documented and justified.
- Initial time must be invested to clearly define the project boundaries. This enables adequate planning of any required inventory and all required monitoring after the project commences.

Step 2: Stratify project area

Stratification is the division of the assessment area into discrete units or populations according to the variables driving variability. Stratifying the area makes sampling more efficient and more cost-effective.[50] Understanding the landscape and its strata generates the 'activity data' (e.g., agricultural practices or scale, among others) necessary to estimate the total carbon benefits of the project. Collecting the appropriate activity data for the project is key to reduce uncertainty associated to the carbon benefit or emission estimates.

Examples of relevant variables affecting soil carbon stocks in agricultural settings include climate, vegetation, topography, management practices, and soil type. Useful resources to stratify an area are regional and global datasets, aerial photographs, satellite imagery, or site information. A list of global and regional databases to support stratification is available in the Resources Annex of this Sourcebook. Furthermore, if the goal of the sampling is to assess changes on carbon stocks over time, stratification approaches should take into account any variability on how different strata might change over time, e.g. consider if changes will occur across all areas or just a subset of them.

Stratification occurs before sampling, with the number of sample units predetermined through estimates of the variance in each stratum. However, post-stratification can be used where unexpected results are attained. A new stratification results in lower uncertainty in the final calculated soil carbon numbers. When measurements are taken in a time-series, however, changing the stratification after each event can be difficult and raise inconsistencies in data comparability.

Recommendation:

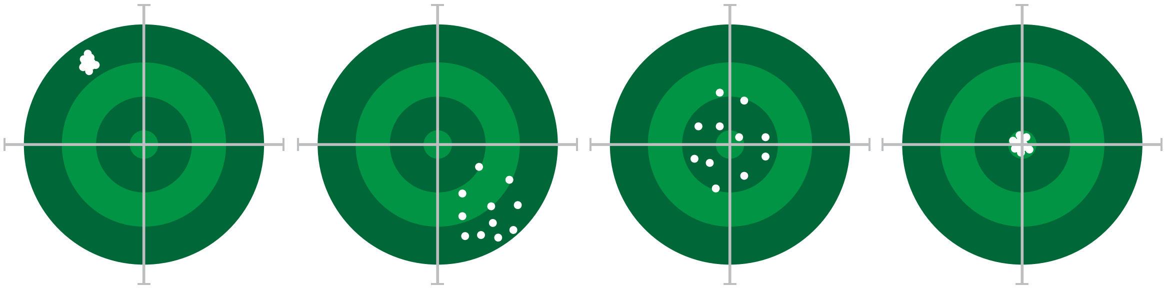
- The site should be stratified by management practice to differentiate impacts on soil carbon stocks. If the area is affected by distinct topography or soil types, it is recommended to stratify the site accordingly to tease out their impact on soil carbon stocks. If the area of interest is large enough to present different climatic regimes, it should be stratified by climate and management practice at a minimum.

Step 3: Develop a sampling design

1 ASSESSMENT BOUNDARIES
2 SITE STRATIFICATION
3 SAMPLING DESIGN
4 SAMPLING FREQUENCY

The focus of the soil carbon assessment will determine the level of accuracy needed and thus the design of the assessment.

It is important to understand the difference between accuracy and precision; *accuracy* refers to how close measurements are to the actual value, while *precision* denotes the closeness of repeated measurements to each other. A frequently used analogy to represent the differences between accuracy and precision is the bull's eye on a target (Figure 16). Ideally, measurements on soil carbon would be accurate, so they represent actual carbon stocks, and precise, so the error or confidence interval of the estimate is small. Consistent inaccuracy would be an indication of a bias or systematic error, while imprecision is associated with random errors.[36]



INACCURATE BUT PRECISE

INACCURATE AND IMPRECISE

ACCURATE BUT IMPRECISE

PRECISE AND ACCURATE

Figure 16. Representation of accuracy and precision.

While it is expected that the larger the number of sample units, the lower the error associated with the estimate will be, it is not realistic to plan for unlimited replicates. Understanding the goal of the carbon assessment and being conservative when designing the approach is important to ensure goals are met cost-effectively. Samples are collected to understand the population or strata by selecting a few points or observations that are representative of the entire population.

How many sample units to collect

- The precision required has a direct effect on costs, as higher precision means more sample units collected. Taking enough sample units to target a 10% uncertainty under a 90% confidence level is recommended.[10]
- Taking three replicates per stratum as an initial assessment is the recommended approach prior to developing the sampling plan to get an indication of the variance in each stratum. Box 3.5 provides guidance to estimate the number of samples needed for a pre-specified level of accuracy.

Where to collect sample units

- The most common approach in field studies is a systematic sampling using transects or grids within each stratum, where either all or a random selection of them (meeting number of sample unit needs) are sampled (see options in Figure 17). Alternatively, a GIS procedure could be employed to randomly select sampling points. Sampling locations should never be selected by the field team in the field as bias cannot be avoided.
- The points where soil cores are being extracted could be a single point or a cluster of sampling sites, and should be recorded with a GPS device.[11]

When to collect the sample units

- While the seasons of the year might not have a direct effect on soil carbon stocks, they affect vegetation and land management practices in agricultural settings that, in turn, drive carbon inputs to the soil. When soil sample units are collected more than once in the same site (see *Step 5 on Sampling Frequency*), they should be collected during the same season to ensure comparability of results.
- Furthermore, seasons might determine site accessibility and field safety, and field campaigns should be planned accordingly.
- Depending of the number of samples and the temporal variability at the site, the sampling could be planned as a multi-stage or muilti-phase sampling as long as comparability between sampling events is guaranteed.

BOX 3.5 DETERMINING THE NUMBER OF SAMPLE UNITS TO COLLECT

A key step in the design of soil carbon assessments is to determine the number of sample units that need to be collected from the field (i.e., sample size) to achieve the desired pre-specified level of accuracy.[117] Having prior knowledge of the soil carbon variability in the site is necessary to determine how many sample units would meet the desired accuracy.

The sample size *(n)* in a simple random sampling approach can be calculated from a known margin of error (relative error, *dr*), sample mean, and coefficient of variation *(CV)* as follows[117]:

$$n = \left[\frac{t_\alpha \times CV}{d_r}\right]^2$$

Where is the Student *t* factor for a given confidence level α. Additional guidance to calculate relative errors and confidence levels is provided in Box 3.3 *Statistical Measures and Uncertainty Assessment*.

When soil carbon variability is not known and preliminary sampling is not possible, a moderate coefficient of variation for SOC (~25%)[117] can generally be expected and used.

Figure 17 can be used to estimate the number of sample units needed to achieve an intended relative error at a selected confidence level. For example, a 10% relative error in a 0.90 confidence level for SOC of 20% coefficient of variation would require approximately 12 cores.

Confidence level	Relative error, d_r	Coeffiicient of variation (CV), %					
		10	**20**	**40**	**50**	**100**	**150**
0.80	0.10	2	7	27	42	165	370
	0.25			6	7	27	60
	0.50				2	7	15
	1.0					2	4
0.90	0.10	2	12	45	70	271	609
	0.25			9	12	45	92
	0.50				2	13	26
	1.0					2	8
0.95	0.10	4	17	63	97	385	865
	0.25			12	17	62	139
	0.50				4	16	35
	1.0					9	16

Figure 17. Guidance on sample sizes required for using a pre-specified relative error and coefficient of variation, from Pennock et al 2006.

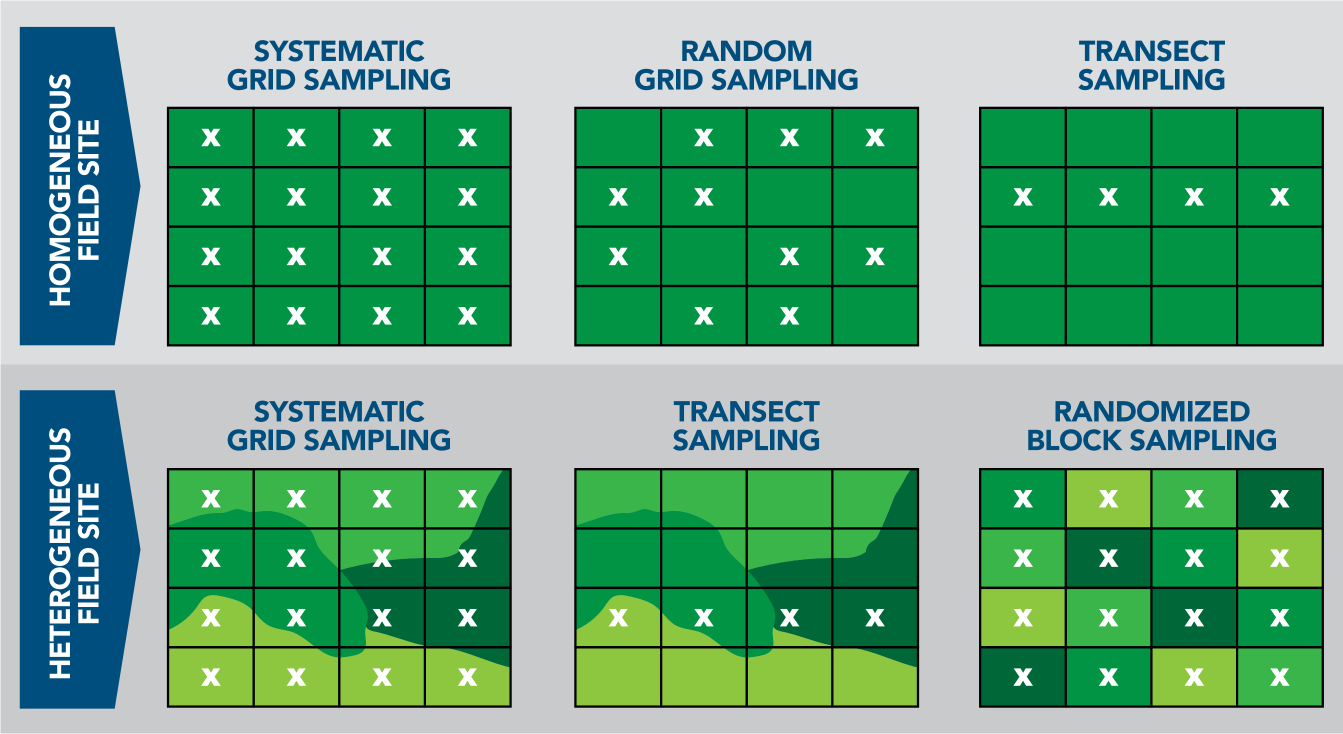


Figure 18. Options for laying out soil sampling points in agricultural fields. Colors represent strata or treatments. The transect approach can be modified to a zigzag design.

Once developed, the sampling design must be compiled into standard operating procedures to guide the field crew, with detailed instructions that ensure consistent sampling across sites and over time.

Recommendations:

- The selection of points should be as low as possible to achieve the desired goal of the assessment under the required level of precision. Over-sampling would result in inefficient use of resources, while under-sampling would lead to statistical errors.
- Collect soil samples after crop harvest and avoid sampling after recent soil nutrient amendments. All sample units must be collected at similar times or seasons to ensure comparability of conditions and results.

Step 4: Determine sampling frequency

1 ASSESSMENT BOUNDARIES
2 SITE STRATIFICATION
3 SAMPLING DESIGN
4 SAMPLING FREQUENCY

Sampling frequency in carbon assessments is defined by the expected rate of change in the carbon pool with intervention, managerial or budgetary restrictions, and/or seasonality. If a soil site needs to be resampled, new sample units should be collected as close as possible to the original sites for the highest sensitivity, as long as the integrity of the site is guaranteed.

Sample units must be retaken over a period that ensures the comparison with initial sampling conditions is meaningful, i.e., when enough time has passed for the implemented management practice(s) to make an impact on soil carbon stocks. Soil carbon stocks can take years to effectively change; while the impact on soil carbon is immediate, changes occur slowly until a new soil equilibrium is reached. The Intergovernmental Panel on Climate Change (IPCC) recommends[51] assuming a 20-year period for new soil equilibrium to be reached after land management or land cover change.[45,52] Typically, annual measurements will not be able to capture changes in carbon stocks and instead remeasurement will be most efficient every 5 to 10 years.

Because of the costs associated with sampling, resampling might not be cost-effective. Carbon assessments seeking to generate verifiable carbon credits, however, might need to take additional sample units during the monitoring period to ground truth modeled changes in soil carbon stocks. The frequency and requirements to do so are provided in detail in the approved methodologies of the standard of choice.

MODULE B: SOIL CARBON MODELING APPROACHES

There are many instances where direct measurements are not practical or cost-effective. These can include cases where soil carbon is not the main focus of activities, where resources such as time and equipment are limited, and where activities span large areas such as whole farms, grazing lands, landscapes, or even regions, which can make it difficult to access sampling locations or would require many sample points to be representative. Direct measurements also may not provide all the information necessary to answer questions on future carbon stocks and changes in soil carbon dynamics. In such cases, models can be used to estimate how soil carbon stocks will change with land use and management. Such models seek to represent the impact of land use, management, and environmental variables on soil carbon dynamics in areas where soil carbon stocks have not been or cannot be measured. Models can also be used as part of an integrated approach in conjunction with measurement campaigns (Module A) and remote sensing methods (Module C), which can provide the data needed to drive them. They can be used to scale up measurements across larger areas and to make predictions of soil organic carbon change in future scenarios.

Model calibration and continuous improvement typically uses field measurements (see Module A) to improve assessments and reduce uncertainties. Recent technological innovations (see Module C) and growing soil databases (see Annex) will likely improve data availability and accuracy.

Soil carbon models account for the main factors which determine soil carbon change. Factors can be split into two groups:

(1) **Edaphic factors**: These are the physical and chemical properties of the soil itself, which are determined by soil type and climate. They are essentially dependent on location.

(2) **Anthropogenic factors**: These are land use and land management factors that influence the build-up or breakdown of soil carbon and are dependent on human activity. They include any activities that change land cover. Native ecosystems tend to hold the maximum amount of soil carbon possible, as soils have reached equilibrium. Change from a native ecosystem such as forest land or native grassland to annual cropland therefore typically results in a loss of soil carbon. Conversely, a change from a managed land such as annual cropland back to a native ecosystem should lead to a build-up of soil carbon as a new equilibrium is reached. For managed lands, as explained in Chapter 1, management activities can add carbon to the soil (by increasing plant material or manure inputs) or lead to the loss of soil carbon through activities that increase the rate of decomposition such as tillage. Details of different land management activities that have a positive impact on soil carbon are given in Chapter 1.

Models are designed to capture the effects of these management practices on different soil types in different climate conditions. Management practices and the locations in which they occur are therefore inputs to soil carbon models, along with information on soil type and climate. This module is divided into:

- ***Part A***: Types of soil carbon models and when to use them
- ***Part B***: Guidance for the three most common calculators which use the IPCC empirical model
- ***Part C***: Guidance on choosing a process-based model

PART A: TYPES OF SOIL CARBON MODELS AND WHEN TO USE THEM

Models which estimate soil carbon stocks and changes can be either:

Empirical models	• Calculations based on sets of equations derived from observed relationships between environmental and management 'factors'.
Process-based models	• Simulations of the processes likely to affect soil carbon stocks (plant growth, decomposition, water balance, nutrient turnover etc.)

Empirical models

Empirical soil carbon models use relatively simple equations which assume soil carbon changes in a linear fashion. The most widely used example is the computational method developed by the Intergovernmental Panel on Climate Change (IPCC). The method was originally developed for use in national scale GHG inventories.[37] The method computes projected net stock changes of carbon over a given time period in a one-step process (e.g., one stock for year 1 and another for year 20). The method assumes a linear rate of change over time with the default time period being 20 years. Therefore, it does not capture long-term changes in soil carbon.

Tier 1 approach

The IPCC method uses information on climate, soil type, and land use/management (tillage and productivity) to relate land management activities to soil carbon stock changes. Users supply 'Activity Data', i.e. the information on land use and management activities and where they take place, and this is used to calculate stock changes using stock change 'factors'. If the IPCC default factors are used, this is referred to as a **Tier 1 method**. The defaults are quite generalized, and the results produced can therefore have a high level of uncertainty (Table 6).

The Tier 1 IPCC method can therefore be suitable for situations where data is scarce such as:

- An ex-ante assessment for a project proposal
- A quick scoping study to help choose potential land management interventions
- Large studies where data may be scarce (e.g., some countries' national inventories)
- A quick assessment in a project where a broad estimate of soil carbon change is acceptable to the recipient (this could be a report to a funding agency for a project where soil carbon increase is not the main focus. Users should always check with an agency first.)

Tier 2 approach / Empirical model-based calculator

The IPCC Tier 2 method allows users to replace some IPCC defaults with their own project/site-specific 'factors' on soil organic carbon stocks under native vegetation or land management (tillage and productivity). It can also allow more detailed activity data to be used. This allows users to reduce uncertainty and make estimates more site-specific. If using an empirical method, users are encouraged to use a Tier 2 approach wherever possible. A combination of some default and some site-specific factors will usually be used. For more information on stock change factors see the 2006 Guidelines for National Greenhouse Gas Inventories – Volume 4.[37]

The IPCC Tier 2 method can be useful in situations where site-specific information is available, but users do not have access to the expertise and detailed data needed to use a process-based model.

Case study 3.: use of an empirical model by EthioTrees

EthioTrees carries out woodland restoration in the northern region of Tigray in Ethiopia.[118] The project's estimates of future soil carbon sequestration rely on peer-reviewed, published literature from the region. An empirical model that accounts for local soil and aboveground carbon dynamics was developed in the project region by Mekuria et al. in 2011. To use the estimates from this model, EthioTrees has set 10 conditions that all sites must meet, whether sites are already in the project description or are candidates to expand the project.[118] Every five years, the project plans to reassess soil carbon with field sampling to compare levels to initial estimates.

An example could be land management projects wanting to report on climate change mitigation impacts that can collect site-specific information. As the Tier 2 method is still quite straightforward, it can also be useful in situations where different land management scenarios need to be compared (e.g., comparing the impact of a project with a business as usual scenario).

Process-based models (Tier 3)

Process-based models simulate processes that govern soil carbon turnover, accounting for the underlying dynamic processes determining soil carbon stocks.

A Tier 3 approach is more demanding and detailed than Tier 1 and 2, usually relying on process-based models. Process-based models simulate the *processes* that govern the turnover of soil carbon in the soil. They take account of the underlying dynamic processes determining soil carbon stocks and are therefore also sometimes referred to as Dynamic Models. Some include sub-models of plant growth which are used to estimate inputs to the soil (leaf litter, crop residues, roots, root exudates, etc.) while others require the user to provide these inputs. All include a representation of the way soil organic matter breaks down, which ultimately determines soil carbon content. In process-based models, soil carbon is divided into pools with different decomposition rates, ranging from days to centuries.[53] This allows them to account for the slow changes in soil carbon which result from historical events such as land use change.

BOX 3.6 ADVANTAGES OF PROCESS-BASED MODELS

Advantages of process-based models include:

- Significantly lower uncertainty than empirical models,
- Ability to allow land use and land management histories to be taken into account when projecting soil carbon stocks of the future, and
- Ability to use detailed site-specific data (climate, soil type, land use history, land use, and management) to produce accurate results.

Process-based models were originally developed for use in temperate conditions, so may need to be parameterized (checked and set up) for use in non-temperate conditions (if they have not been already). As process-based models provide more accurate results, they may also be stipulated for use with certain carbon certification schemes. When linked to a Geographic Information System (GIS) they can be used to identify geographic areas of carbon release, or potential for carbon sequestration.[54,55] As process-based models require a significant degree of site-specific information, there are currently very few examples of them being used in tools and calculators (see Case Study 3.2).

Table 6. Types of soil carbon models and when to use them

	Empirical models		Process-based models
	IPCC Tier 1	**IPCC Tier 2**	**(Tier 3)**
Effort	Lowest	Medium	High
Expertise	Low	Medium	High
Data inputs needed	Activity data	Activity data and site-specific stock factors (e.g., soil carbon stock under native vegetation)	• Activity data (current and historical) • Soil data • Climate data • Long-term experiments to check model is applicable to site
Accuracy	Low	Improved	Further improved
Soil depth	30 cm	30 cm	Varies (20cm for most but can be up to 100cm)
Example of when to use	• Project proposals • Scoping studies comparing general scenarios • Situations where data is scarce (e.g., soil carbon not the focus or large scale)	• Land management projects wanting to report on climate change mitigation impacts and able to collate site specific data • Comparing land management scenarios	• For accurate estimates of long-term soil carbon change • Where low uncertainty is needed to report to a donor or private sector investor • If the use of a certain model is required by a carbon certification scheme
Constraints	High uncertainty	• Some site-specific inputs needed • Moderate uncertainty	• Detailed site-specific data needed • Parameterization data may also be needed using local long-term data sets

Case study 3.2: use of a process-based model by Pastures, Conservation and Climate Action, Mongolia

The Pastures, Conservation and Climate Action (PCC) project, funded by the Darwin Initiative and developed by the University of Leicester in partnership with MSRM (the Mongolian Society for Range Management) under the Plan Vivo Standard, implements improved grazing practices in rural Mongolia. The project used the CENTURY model to estimate conservative soil organic carbon sequestration rates during project implementation under different pasture types and grazing scenarios.[119] Estimates are based on local management, climate, vegetation, and soil conditions, and will be updated at the end of each commitment period based on limited soil sampling to compare soil carbon stocks to model predictions.[119]

PART B: GUIDANCE FOR THE THREE MOST COMMON CALCULATORS WHICH USE THE IPCC EMPIRICAL MODEL

Several calculators have been developed which use the IPCC empirical method to estimate changes in soil carbon stocks. Although the use of these calculators may be associated with high uncertainties, they provide a simple, low-cost, and user-friendly option to make an estimation of soil carbon changes more accessible. Most of these calculators give the net greenhouse gas (GHG) or carbon balance of land management activities e.g., all changes in carbon stocks and GHG emissions from all land-based activities including changes in soil organic carbon, biomass carbon, and GHG emissions. A recent report by the World Bank[56] compared the relative performance of some of these calculators for net GHG accounting. They found each tool to be suited to different remits and conditions depending on the sources and sinks being considered. Here we consider the following three of the tools recommended by the World Bank report and are the most widely used to estimate changes in SOC in a range of land uses (Table 7):

- Carbon Benefits Project (CBP)
- EX-ACT carbon balance tool
- Cool Farm

All these calculators cover croplands, rangelands or grazing lands, grasslands, agroforestry practices, forest lands, wetlands, and rice cultivation. In addition to these land types, Cool Farm covers horticultural practices and orchards. Calculator guidelines are available in multiple languages for broad accessibility.

These calculators are described in detail below, with detailed background information and step-by-step guidance and recommendations on how to use them. For a more in-depth tool comparison, the reader is referred to Toudert et al.[56]

Recommendations:

- Users are encouraged to use Table 7 for a quick guidance to choose between the three tools considered, which summarizes further basic information about the tools.
- Users are encouraged to consider land use types they are working with, languages the tools are available in, whether the tool can be used online, etc.
- Because many more tools are available, users are encouraged to read the World Bank's guidance document on 'Greenhouse Gas Accounting Tools for Sustainable Land Management'22,56 for guidance on choosing from a wider selection of tools to estimate soil carbon change.

Table 7. Overview of three calculators widely used to estimate changes in soil organic carbon, Carbon Benefits Project (CBP), EX-ACT, and Cool Farm.

			ADDITIONAL ATTRIBUTES				
CALCULATOR	**HOW TO ACCESS**	**SCALE DESIGNED FOR**	**SPATIAL OUTPUT**	**UNCERTAINTY**	**LEAKAGE**	**SOCIO-ECONOMIC TOOLS**	**NON LAND USE GHGS (ENERGY & FUEL USE)**
CBP	Online	Landscape	●	●	●	●	
EXACT	Download	Landscape		●	●	●	●
COOL FARM	Online	Farm					●

CALCULATOR	DATA REQUIREMENTS	TIME REQUIREMENTS	SKILLS REQUIREMENTS
CBP	Medium	> 30 minutes	High
EXACT	Medium	< 30 minutes	High
COOL FARM	Medium	< 30 minutes	Very High

CALCULATOR	INCLUDED CARBON POOLS				
	ABOVE GROUND BIOMASS	BELOW GROUND BIOMASS	LITTER	DEAD WOOD	SOC
CBP	●	●			●
EXACT	●	●	●	●	●
COOL FARM	●	●			●

The accuracy of a calculator depends on the data that the user enters in it. The data requirements of these calculators (Table 7 above) can be supplied at plot or farm scale by the farmers or land managers. At a regional scale, however, databases and inventories are usually needed, along with expert knowledge to avoid using data that results in high uncertainties.[56]

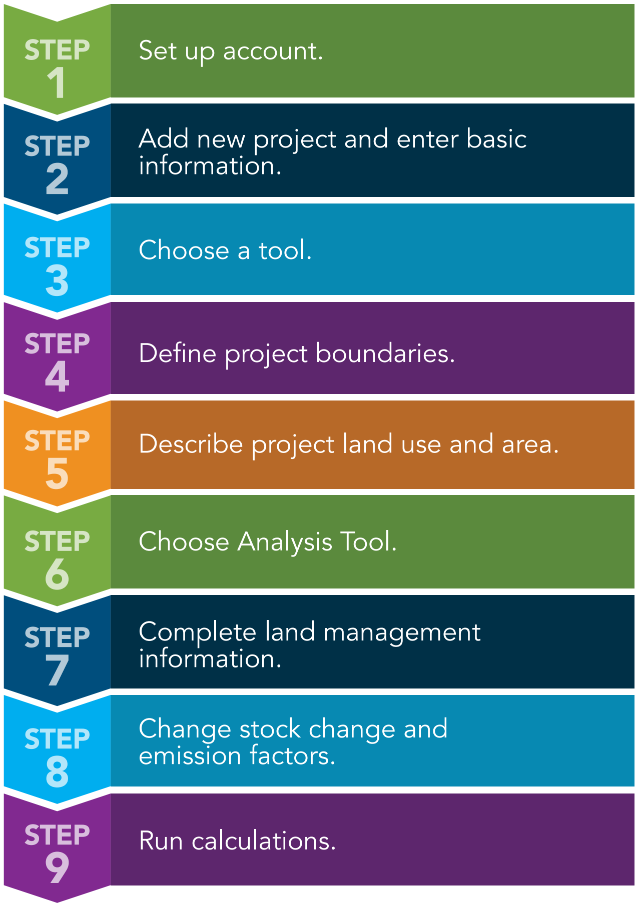
1. Carbon Benefits Project (CBP)

CBP was originally designed to be used for landscape-scale projects with a mix of different land uses and management activities.

The Carbon Benefits Project (CBP) was developed by Colorado State University and partners including the United Nations Environment Programme (UNEP), with funding from the Global Environment Facility (GEF). It estimates the change in soil carbon stocks due to land use and management activities (project scenario) compared to a business as usual situation (baseline scenario) over the same time period. users need to have compiled 'activity data' before using the tools. Templates for collecting activity data for different land use categories can be found on the CBP website. An overview of how to use the CBP tool is presented in Figure 19.

Recommendation:

- Download the templates for collecting activity data for different land use categories from the CBP website.57



STEP 1 Set up account.

STEP 2 Add new project and enter basic information.

STEP 3 Choose a tool.

STEP 4 Define project boundaries.

STEP 5 Describe project land use and area.

STEP 6 Choose Analysis Tool.

STEP 7 Complete land management information.

STEP 8 Change stock change and emission factors.

STEP 9 Run calculations.

Figure 19. CBP step-by-step guide (based on the CBP Quick Guide on the CBP website)

Step 1: Set up account

Go to ‘Access tools’ tab on carbonbenefitsproject.org.[57]

Step 2: Add new project and enter basic information

For example, this could include project name, time period, applicable countries. Choosing the country/ies is very important as this will take you to a map in the next steps.

Step 3: Choose a tool

Click on ‘Tool Kit Advisor’ and choose a tool. The Detailed Assessment follows a Tier 2 approach, allowing users to input their own site-specific stock change and emission factors.

Recommendations:

- For circumstances relevant to this sourcebook, reporting should take the Detailed Assessment approach.

Step 4: Define project boundaries

You can define multiple areas by drawing points or polygons on a map or uploading points or GIS files.

Recommendation:

- Using points is good if you want to represent multiple smallholdings. These can be linked if land use and management is the same for all of them. Polygons are useful if you want to represent larger areas, such as areas of avoided deforestation.

Step 5: Describe project land use and area

Enter the number of years you want to create a report for (can be equal to, shorter, or longer than the project length). For each polygon, point, or group, enter land area under different land use categories.

Recommendation

- This step needs to be done for the initial situation before your project started (Initial land use) and for the situation at the end of the reporting period under your **Project scenario** and under a **Baseline scenario**.

Step 6: Choose Analysis Tool

Go to ‘Analysis Tools’ and choose the ‘Detailed Assessment’. You will be taken to the tools home page. Click on ‘Initial Land Use’ to get started.

Step 7: Complete land management information

Fill in relevant information for each ‘Project activity area’ (points, polygons or groups of these) for the Initial Land Use, the Baseline Scenario, and the Project Scenario. Land use categories requiring data will be marked with a red cross (‘X’). Choose from a drop-down list or create your own (select new ‘types’ and change any stock changes or emission factors to alter inputs to the soil).

Step 8: Change stock change and emission factors

You can see a list of all factors involved in the calculations (name, type, units, source, etc.) under the land use category you are working in, such as dry matter of residue left in the field, yield, or residue to yield ratio as factors. You can change the soil carbon factor.

The soil carbon factor is the equilibrium soil carbon under native conditions.

Step 9: Run calculations

Run the calculations to create either a summary report (PDF) or a detailed report (Excel file). The summary report (Figure 20) gives net GHG balance, including soil carbon stock change under a baseline scenario, a project scenario, and the difference between the two. All results are in t CO_2e ha^{-1}, broken down by project area.

Recommendation

- Make sure all required data inputs for land management in all land use categories in all project activity areas under all scenarios have a green check (‘√’) by the side and that you receive a message saying data entry is complete.

Figure 20. Example of a simple summary CBP report

Greenhouse Gas Source and Sink Categories	Baseline Emissions (2010)				Project Emissions (2020)				Carbon Benefits		
	CO_2	CH_4	N_2O	GHGs	CO_2	CH_4	N_2O	GHGs			
	tonnes CO_2 equivalent				tonnes CO_2 equivalent				Total tCO_2e	tCO_2e/ha	tCO_2e/ha/yr
AGRICULTURE											
A. Enteric Methane		2698.5				6746.25			40477.5	1.686563	0.168656
B. Manure Management		116.34	2046			290.85	5115		32435.1	1.351462	0.1351462
C. Rice Cultivation		0				0			0	0	0
D. Agricultural Soils	0	0	2480.93		0	0	6201.86		37209.3	1.550388	0.1550387
E. Prescribed Burning of Savannas		0	0			0	0		0	0	0
F. Field Burning of Agricultural Residues		0	0	0		0	0	0	0	0	0
G. Other	0	0	0	0	0	0	0	0	0	0	0
LAND USE CHANGE AND FORESTRY											
A. Forest and other Woody Biomass	0				-63869.63				-638696.3	-26.61235	-2.661235
B. Forest and Grassland Conversion	0	0	0	0	0	0	0	0	0	0	0
C. Abandonment of Management Lands	0				0				0	0	0
D. CO2 Emissions and Removals from Soil	0				-41800				-418000	-17.41667	-1.741667
E. Other	0	0	0	0	0	0	0	0	0	0	0
TOTAL	0	2814.84	4526.93	0	-105669.6	7037.1	11316.86	0	-946574.4	-39.4406	-3.94406

2. The Cool Farm Tool

The Cool Farm tool was developed by the University of Aberdeen and the Sustainable Food Lab for Unilever. It provides net Carbon Balance (including soil carbon) and was developed for commercial food and drink companies, farmers, co-operatives, and development agencies in temperate and tropical climates. It uses activity data provided by the user and the IPCC default values supplemented by some Tier 2 data from published studies. Guidance on collecting activity data needed to drive the tool is provided in the user guide. It is was originally developed for growers producing annual crops but has been extended to cover other land use types, including grazing lands, grasslands, agroforestry, forests, wetlands, rice cultivation fields, horticulture, or orchards. It is suited to the analysis of carbon stock change for individual fields under single crops. However, multiple runs can be set up for farm/landscape scale analysis. The step-by-step guidance below (outlined in Figure 21) therefore refers to annual cropland.

STEP 1 Set up account.

STEP 2 Enter general information about the crop to model.

STEP 3 Enter growing area and soil characteristics.

STEP 4 Enter field treatment.

STEP 5 Enter management characteristics.

STEP 6 Produce summary report.

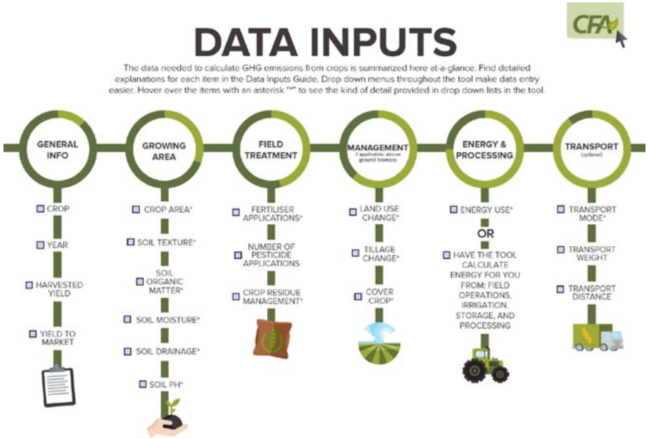
Figure 21. Cool Farm Tool step-by-step guide, based on the Cool Farm online user guide

Step 1: Set up an account

Go to www.coolfarmtool.org/CoolFarmTool[58] and choose ‘Greenhouse Gases’.

Step 2: Enter general information about the crop to model

For example, these could include baseline year, crop type, total annual harvested yield, etc. (see Figure 22).



The data needed to calculate GHG emissions from crops is summarized here at-a-glance. Find detailed explanations for each item in the Data Inputs Guide. Drop down menus throughout the tool make data entry easier. Hover over the items with an asterisk "*" to see the kind of detail provided in drop down lists in the tool.

Figure 22. Inputs to the Cool Farm Tool (from the Cool Farm Tool website[39]).

Step 3: Enter the growing area and soil characteristics

Record the area on which the crop is grown (Growing Area in Figure 22) and soil characteristics for this area as shown in Box 3.7.

Step 4: Enter field treatment

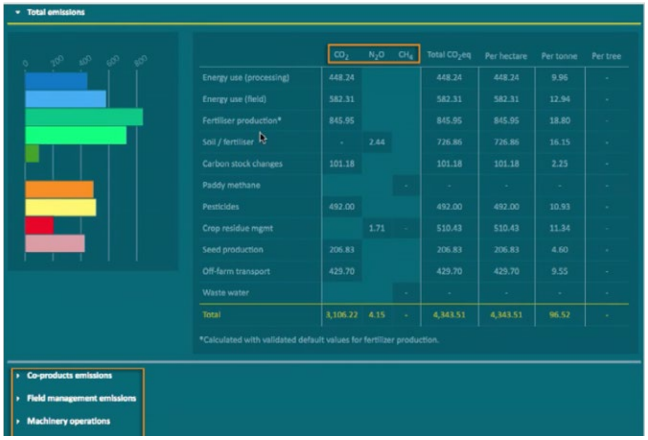
Enter information on fertilizer application rates (for both chemical fertilizer and manure) and pesticide use. Also, record crop residue information including the amount of crop residue produced (weight of dry matter), and choose an option for how it is managed (incorporated in the field, burned, removed, etc; seeFigure 22).

Step 5: Enter management characteristics

Enter information about land management for the given area (e.g., state if land use has been converted to or from arable land grassland or forest in the past 20 years, provide information on changes in tillage or use of cover crops). Enter information about energy use and transport before net GHG emissions and stock changes including soil carbon can be calculated.

Step 6: Produce a summary report

The system provides a summary report page with net GHG emissions and carbon stock change (Figure 23). If the information has only been for annual cropland, carbon stock change will be soil carbon only. There is also an option to export data as an Excel file for further analysis.



	CO_2	N_2O	CH_4	Total CO_2eq	Per hectare	Per tonne	Per tree
Energy use (processing)	448.24			448.24	448.24	9.96	-
Energy use (field)	582.31			582.31	582.31	12.94	-
Fertiliser production*	845.95			845.95	845.95	18.80	-
Soil / fertiliser	-	2.44		726.86	726.86	16.15	-
Carbon stock changes	101.18			101.18	101.18	2.25	-
Paddy methane			-	-	-	-	-
Pesticides	492.00			492.00	492.00	10.93	-
Crop residue mgmt		1.71	-	510.43	510.43	11.34	-
Seed production	206.83			206.83	206.83	4.60	-
Off-farm transport	429.70			429.70	429.70	9.55	-
Waste water			-	-	-	-	-
Total	3,106.22	4.15	-	4,343.51	4,343.51	96.52	-

*Calculated with validated default values for fertilizer production.

Figure 23. Example of a Cool Farm Tool summary report

BOX 3.7 SOIL CHARACTERISTIC INPUTS FOR THE COOL FARM TOOL

Users will need to collect information on different soil characteristics, outlined in the table below, in advance of using the Cool Farm Tool.

Characteristic	Detail
Soil texture	**Fine** = sandy clay, silty clay and clay **Medium** = sandy clay loam, clay loam and silty clay loam **Coarse** = sand, loamy sand, sandy loam, loam, silt loam, and silt
Soil organic matter (%)	SOM ≤ 1.72 ; 1.72 < SOM ≤ 5.16 ; 5.16 < SOM ≤ 10.32 ; 10.32 > SOM
Soil moisture	Dry | Moist
Soil drainage	Poor | Good
Soil pH	pH ≤ 5.5 ; 5.5 < pH ≤ 7.3 ; 7.3 < pH ≤ 8.5 ; pH > 8.5

3. Ex-Ante Carbon Balance Tool EX-ACT

The EX-ACT tool was developed by the United Nations' Food and Agriculture Organization (FAO) with funding provided by the World Bank and technical expertise by The French National Research Institute for Sustainable Development. The tool was designed for agriculture and forestry development projects to help them estimate the impacts of their activities on net GHG balance e.g., all GHGs emitted or sequestered due to project implementation as compared to a business-as-usual scenario, including changes in soil carbon. The tool is driven by activity data supplied by the user, and it uses the IPCC method with options to use default Tier 1 factors and or region-specific coefficients (Tier 2). EX-ACT is a Microsoft Excel-based tool which can be downloaded free of charge. An overview of how to use the EX-ACT tool is presented in Figure 24.

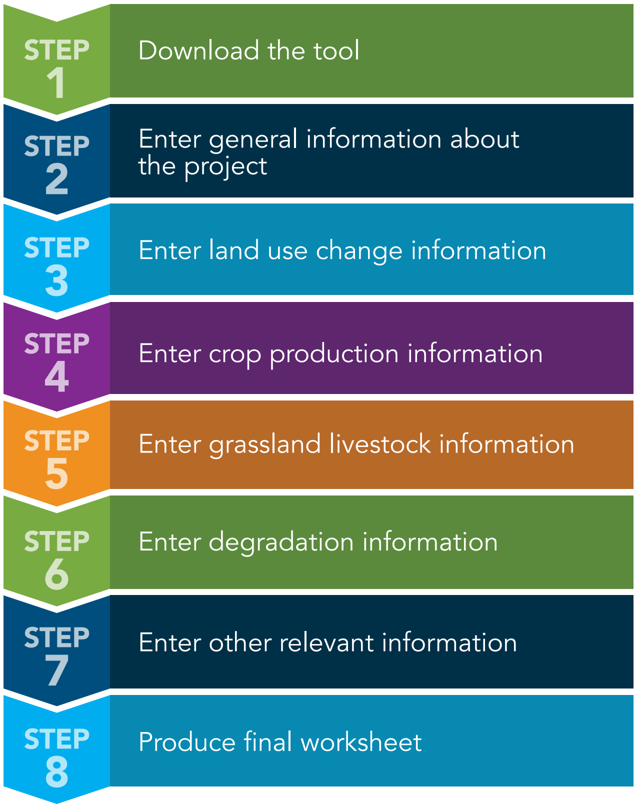


Figure 24. EX-ACT step-by-step guide, based on WB e-learning courses on GHG accounting tools

Step 1: Download the tool

Download the tool from the EX-ACT website at www.fao.org/in-action/epic/ex-act-tool/en/[40] and register.

Step 2: Enter general information about the project

In the 'Project Description' tab, enter the project name, location, area of the site, climate, and soil type, and choose a timeframe for the analysis. The EX-ACT tool then takes the user through a series of worksheets where project 'activity data' is entered.

Step 3: Enter land use change information

Enter information on how land use changes over time for a business as usual and a project scenario.

Land use change covers changes from one land use to another, such as forestland to cropland, rather than changes in land management.

Step 4: Enter crop production information

If the area includes annual or perennial crops or rice, click on the 'Crop Production' tab and complete information on the crops grown and management information such as fertilizer inputs, tillage practices, and residue management which all impact soil carbon stocks.

Recommendation

- For all worksheets, this information needs to be completed for a business-as-usual and a project scenario.

Step 5: Enter grassland livestock information

If the area includes grassland, select the 'Grassland Livestock' worksheet and enter information on grassland management, such as the condition of the grassland, fertilizer inputs, and improvements such as irrigation or use of improved varieties.

Step 6: Enter management degradation information

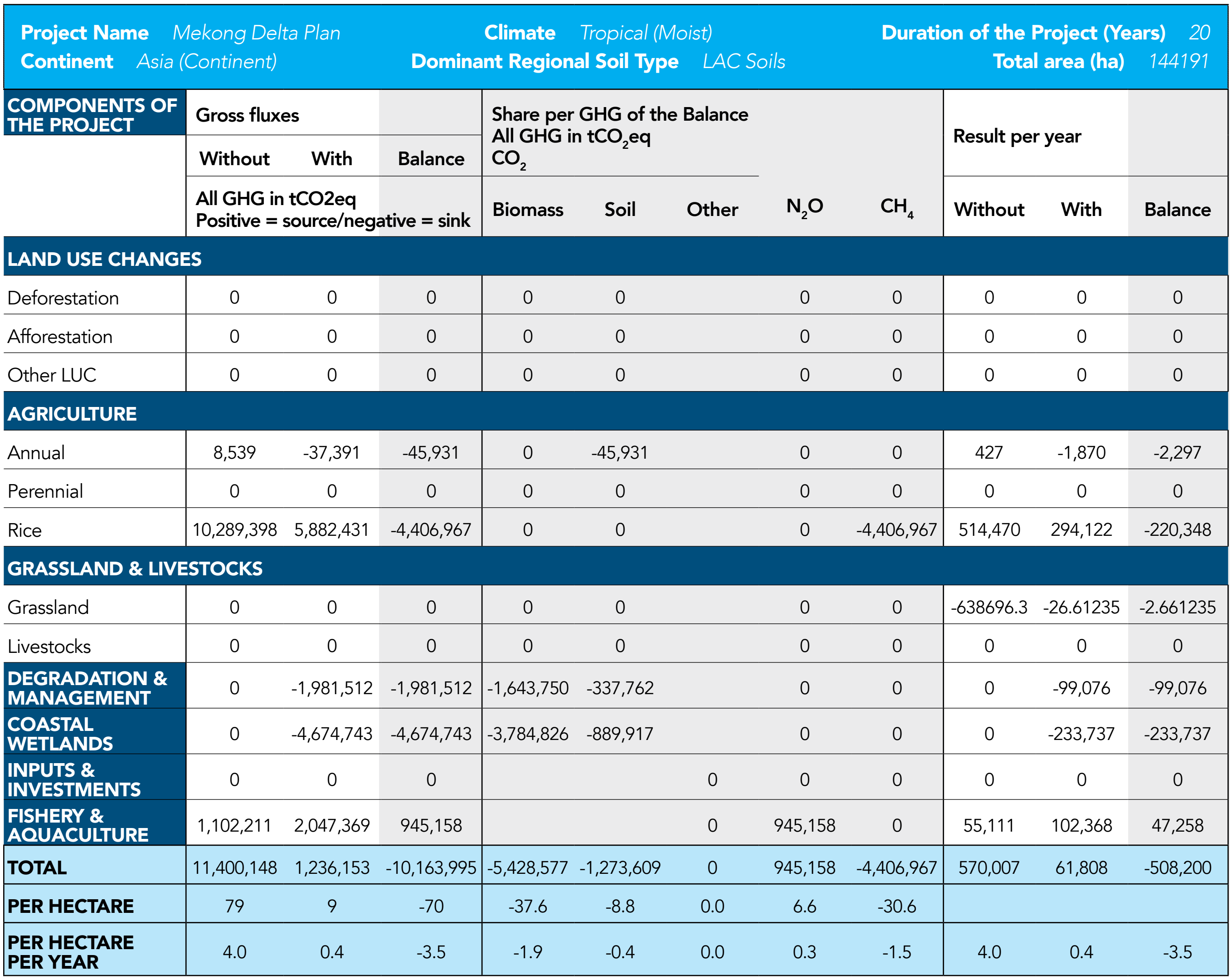
Complete information on forest degradation, drainage of flooded soils, and peat extraction, if applicable to the project site.

Step 7: Enter other relevant information

Add information about coastal wetlands, energy use, and fisheries, if relevant.

Step 8: Produce final worksheet

Once inputs are completed, the final worksheet shows the net GHG balance broken down by land use type. It includes a column specifically for soils giving CO_2 gains or losses by land use (Figure 25).



Project Name *Mekong Delta Plan* **Climate** *Tropical (Moist)* **Duration of the Project (Years)** *20*
Continent *Asia (Continent)* **Dominant Regional Soil Type** *LAC Soils* **Total area (ha)** *144191*

COMPONENTS OF THE PROJECT	Gross fluxes			Share per GHG of the Balance All GHG in tCO_2eq					Result per year		
	Without	With	Balance	CO_2							
	All GHG in tCO2eq Positive = source/negative = sink			Biomass	Soil	Other	N_2O	CH_4	Without	With	Balance
LAND USE CHANGES											
Deforestation	0	0	0	0	0		0	0	0	0	0
Afforestation	0	0	0	0	0		0	0	0	0	0
Other LUC	0	0	0	0	0		0	0	0	0	0
AGRICULTURE											
Annual	8,539	-37,391	-45,931	0	-45,931		0	0	427	-1,870	-2,297
Perennial	0	0	0	0	0		0	0	0	0	0
Rice	10,289,398	5,882,431	-4,406,967	0	0		0	-4,406,967	514,470	294,122	-220,348
GRASSLAND & LIVESTOCKS											
Grassland	0	0	0	0	0		0	0	-638696.3	-26.61235	-2.661235
Livestocks	0	0	0	0	0		0	0	0	0	0
DEGRADATION & MANAGEMENT	0	-1,981,512	-1,981,512	-1,643,750	-337,762		0	0	0	-99,076	-99,076
COASTAL WETLANDS	0	-4,674,743	-4,674,743	-3,784,826	-889,917		0	0	0	-233,737	-233,737
INPUTS & INVESTMENTS	0	0	0			0	0	0	0	0	0
FISHERY & AQUACULTURE	1,102,211	2,047,369	945,158			0	945,158	0	55,111	102,368	47,258
TOTAL	11,400,148	1,236,153	-10,163,995	-5,428,577	-1,273,609	0	945,158	-4,406,967	570,007	61,808	-508,200
PER HECTARE	79	9	-70	-37.6	-8.8	0.0	6.6	-30.6			
PER HECTARE PER YEAR	4.0	0.4	-3.5	-1.9	-0.4	0.0	0.3	-1.5	4.0	0.4	-3.5

Figure 25. Example of results produced by the EX-ACT Tool

PART C: GUIDANCE ON CHOOSING A PROCESS-BASED MODEL

Process-based models can give a more accurate estimate of how soil carbon is changing but require more input information and more expertise to use than the calculators described above. The precision of a model is highly dependent on the quality and quantity of data inputs used to run it.

Process-based models are most suitable for extrapolation and representation of agricultural conditions that might not be well represented in the observational data.[59,60]for soil health and CO2 mitigation, is of increasing interest to a wide audience, including policymakers, NGOs and land managers. Integral to any approaches to promote carbon sequestering practices in managed soils are reliable, accurate and cost-effective means to quantify soil C stock changes and forecast soil C responses to different management, climate and edaphic conditions. While technology to accurately measure soil C concentrations and stocks has been in use for decades, many challenges to routine, cost-effective soil C quantification remain, including large spatial variability, low signal-to-noise and often high cost and standardization issues for direct measurement with destructive sampling. Models, empirical and process-based, may provide a cost-effective and practical means for soil C quantification to support C sequestration policies. Exam-

BOX 3.7 EXAMPLE ESTIMATE OF SOIL CARBON CHANGE

Different soil carbon models are recommended based on project needs. For example:

- If an estimate of soil carbon change needs to include losses from soil erosion by either wind or water, the EPIC model is recommended. EPIC works at the plot scale, but there is also a spatial version of the model (EPIC linked to a GIS) called APEX.
- If users are working in areas with substantial amounts of organic soil, the ECOSSE model is recommended.

ples are described of how soil science and soil C quantification methods are being used to support domestic climate change policies to promote soil C sequestration on agricultural lands (cropland and grazing land While they also require field validation, they can deliver accurate results without requiring frequent direct measurements, facilitating monitoring and verification based on agricultural practices (i.e., "practice-based monitoring") and potentially reducing assessment and monitoring costs when compared to traditional field-based monitoring. These can also be integrated with digital data collection approaches and other technological advancements when appropriate (see Module C), and as long as the technology results in reliable and cost-effective measurements within project needs and scope.

Five process-based models commonly used to estimate soil organic carbon change are listed in Table 8, but many more exist. Deciding which model to use depends on the purpose, time required, data availability, computer capacity, and technical expertise of the user. All models below can be used at the plot scale, with some also having options to link them to a GIS for use at a larger scale.[54,61]natural resource managers and policy analysts (who have the appropriate computing skills Each model was designed for a different purpose and remit. Models can also be used to calculate uncertainty in the provided estimate. The 'notable features' column of Table 8 provides useful information for choosing an appropriate model. Like most models, all five are available to download for free with accompanying guidance manuals.

A useful resource for more information on soil carbon models can be found on the International Soil Modelling Consortium website.[62] The two oldest and most widely employed models (RothC and Century) are considered in more detail in Box 3.8.

Case Study 3.3: Soil Model selection for Kenya Agriculture Carbon Project (KACP)[120]

Both the RothC and Century/DayCent models were considered for the World Bank's Kenya Agricultural Carbon Project (KACP), as both are widely used across the African continent. The RothC model was selected because it proved to be suitable for smallholder agricultural carbon projects with limited data availablity in Sub-Saharan Africa, where the land use is very scattered. The project included cropland, grassland, and agroforestry management, and worked with more than 60,000 smallhoder farmers to gather data on an annual basis that served as input into the RothC model. Input data included information onclimate, farming inputs, soil characterisitcs, and soil management. The model was validated for the target region to derive the local soil organic carbon emission factors. Any increase in emissions for example from checmical fertilizers were subtracted from the total soil carbon sequestration. The methodology required the project to apply the VCS non-permanence risk tool to assess the risk of non-permanence,[41] and determined this risk to be low. This project was the first to issue carbon credits under the Sustianable Agricultrual Land Management (SALM) carbon accounting methodology.[114]

BOX 3.8 IN-DEPTH COMPARISON OF ROTHC AND CENTURY/DAYCENT MODELS

RothC

The oldest model is RothC, which models the turnover of organic carbon in non-waterlogged soils. It models the effects of soil type, soil moisture, temperature, and plant cover on the turnover of soil carbon. It was developed by Rothamsted Research in the UK using data from the long-term agricultural trials at Rothamsted, with archive data going back 170 years for some trials. Many other models are based on RothC and the way it describes the turnover of soil carbon. RothC splits soil organic matter into four compartments, with each having different rates of decomposition. It also includes a small pool of inert organic matter assumed not to break down.[121] Because the model only models processes in the soil and not plant growth, users have to know the amount of organic matter inputs to the soil from plants and manure. For those interested in carbon credits/certification, RothC is recommended for use in the Verified Carbon Standard's manual for **'Adoption of Sustainable Agricultural Land Management'**.

Furthermore, RothC is is one of the most common Tier 2 models used in livestock systems to estimate global and national soil organic carbon estimates, as it is the core model of the new FAO's **Global Livestock Environmental Assessment Model (GLEAM)** that simulates bio-physical processes and activities along livestock supply chains.

Century/DayCent

Century is an entire ecosystem model that simulates fluxes of carbon and nitrogen between the atmosphere, vegetation and the soil.[122] It was developed by Colorado State University in the USA. Unlike RothC, Century includes plant growth sub-models. If existing crop, grass, tree, or forest files exist within the model, users can choose from these. If not, users have the option to create their own. Century works on a monthly timestep and there is also a version called DayCent which works on a daily time-step. It was originally developed using information from The Great Plains in the USA but has been applied to a wide variety of different ecosystems. It has sub-models for croplands, grasslands, and forests and the user 'schedules' management events such as planting, fertilizer addition, tillage, and harvest. Century and DayCent have three compartments for soil organic matter with different decomposition rates (active, slow, and passive). They also include above and below ground litter pools and a pool for the soil litter layer. The outputs include monthly or daily change in soil carbon along with CO_2 from soil respiration.

Table 8. Five process-based models commonly used to estimate soil organic carbon change.

Model	Website	Notable features	Time step	Inputs	Outputs (relevant to soil carbon)
RothC	RothC	**Fairly user friendly**, can be run in forward and inverse modes	Monthly	• Monthly climate data (rainfall, air temperature, and evaporation) • Soil clay content • Monthly plant residues & farmyard manure inputs • Decomposability of plant inputs • Soil cover • Depth of soil layer sampled	• Soil organic carbon • Microbial biomass carbon • CO_2 flux
Century/ Daycent	Century/ Daycent	**Widely applied ecosystem model**, C and N dynamics in mineral and flooded soils	Monthly/ Daily	• Climate data (maximum and minimum air temperature and precipitation – monthly for Century, daily for DayCent) • Soil texture class • Plant nitrogen, phosphorus, sulfur, and lignin content • Initial soil carbon and nitrogen • Land cover/use data (e.g., vegetation type, cultivation/planting schedules, amount and timing of nutrient amendments)	• Soil organic carbon • CO_2 flux from heterotrophic soil respiration,
EPIC/ APEX	EPIC	Includes **soil erosion**	Daily	• Daily climate data • Soil texture class • Land cover/use data (e.g., vegetation type, cultivation/planting schedules, amount and timing of nutrient amendments)	• Soil organic carbon • Soil erosion losses from water and wind
DNDC	DNDC	C and N dynamics in **agroecosystems**	Daily	• Daily climate data • Soil properties (e.g., bulk density, texture, soil carbon content and pH), • Vegetation characteristics • Field management activities	• Soil organic carbon • CO_2 flux from soil heterotrophic respiration • Dissolved organic carbon leaching • CH_4 flux
ECOSSE	ECOSSE	Developed from RothC for **peatland soils,** models soil depth to 5m	Monthly	• Net Primary Productivity • Land Use Type • Optional: soil water, plant inputs, nutrient applications and timing of management operations	• Soil organic carbon • CO_2 losses (aerobic) • CH_4 losses (anaerobic)

Example of a soil carbon calculator using a process-based model: COMET Farm

COMET Farm, developed by Colorado State University, is one of the few examples of a calculator for soil carbon that employs a process-based model and can be used to compare different scenarios. It was developed to allow farmers and ranchers in the United States to see if the adoption of 'conservation' practices would have a positive impact on soil carbon and GHG emissions on their farms.[63] At the moment, it has only been deployed in the United States, but further buildout of the system is possible where sufficient land use history, soil, climate, and land management data are available. Versions for other areas of the world are being developed with the anticipated release of a pilot version in early 2022 for countries in the European Union, with the ambition to subsequently extend to additional regions, including some developing countries.

COMET Farm is an online tool.[64] The steps in Figure 26 outline how to use the tool.

STEP 1 Select the types of activities you are interested in (cropland, pasture, range, orchards or vineyards; agroforestry; and/or forestry).

STEP 2 Choose where in the United States your land is located.

STEP 3 Describe historical and current management of your land by choosing options from a drop-down menu.

STEP 4 Describe management practices such as tillage practices, fertilizer and manure application, irrigation, burning, and liming.

STEP 5 The system produces a GHG balance sheet (including soil carbon change) and compares proposed activities with business-as-usual activities.

Figure 26. COMET Farm step-by-step guide

Finding a modeling consultant

While these models have step-by-step guidance, hiring a consultant familiar with soil carbon models and experienced in using them in projects aimed to reduce soil carbon emissions or increase soil carbon stocks can ensure results are produced in a timely manner and meet technical quality. A consultant may be more familiar with available datasets relevant to the project site and likely will have the technical capacity to identify proxy data variables that can be used in cases of data shortages. Data required to run models pulled from secondary sources may be irrelevant if the timing, format, or amount of data is inappropriate. Consultants also may have access to networks for collaborative data sharing to improve model predictions in cases when local data is unavailable. Further, modeling may require complex software, which may be inaccessible to the project without the help of a consultant. If a project chooses to invest in a consultant to help validate, calibrate, and implement a model, it might face less risk of having estimates rejected from a certification after professional review. Involving an experienced consultant can also help to reduce uncertainty in data inputs to the model.

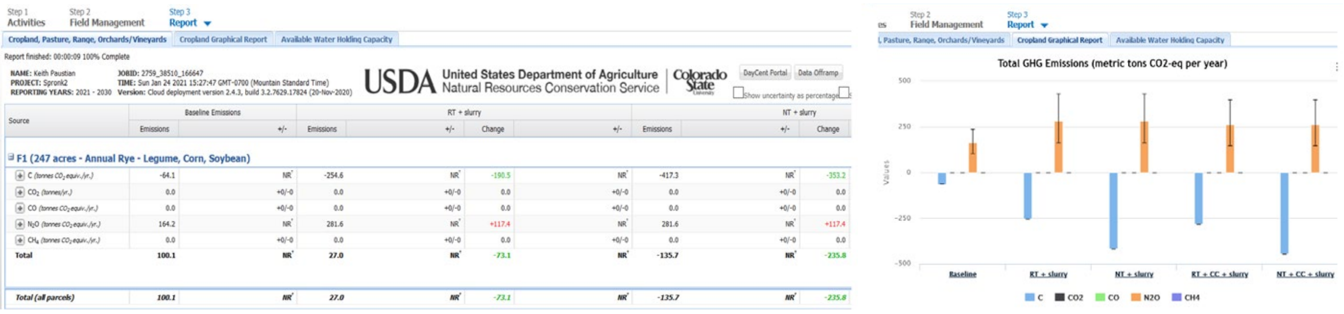
Suitable consultants could be experienced project implementers, academics, or model developers, and they could be contracted from any region in the world since the task does not require in-person work. Consultants can be found by talking to local universities, existing carbon mitigation projects, international development projects, or international agriculture-focused NGOs.

Recommendation:

Once several relevant consultants have been identified, they should be contacted to ask the following questions:

1. What process-based models have you used to estimate soil organic carbon change and in what kind of landscapes?
2. What resources (time and financial resources) would be typically required to complete this type of analysis?
3. What information will you need the project to provide on the area or land management?
4. What is your workflow process when a large volume of data is needed?
5. How do you validate model results?

It is also important to consider the cost and time required to perform modeling analyses, to ensure the project deliverable timeline is met.



Report finished: 00:00:09 100% Complete

NAME: Keith Paustian
PROJECT: Spronk2
REPORTING YEARS: 2021 - 2030
JOBID: 2759_38510_166647
TIME: Sun Jan 24 2021 15:27:47 GMT-0700 (Mountain Standard Time)
Version: Cloud deployment version 2.4.3, build 3.2.7629.17824 (20-Nov-2020)

Source	Baseline Emissions		RT + slurry				NT + slurry		
	Emissions	+/-	Emissions	+/-	Change	+/-	Emissions	+/-	Change
F1 (247 acres - Annual Rye - Legume, Corn, Soybean)									
C (tonnes CO_2 equiv./yr.)	-64.1	NR*	-254.6	NR*	-190.5	NR*	-417.3	NR*	-353.2
CO_2 (tonnes/yr.)	0.0	+0/-0	0.0	+0/-0	0.0	+0/-0	0.0	+0/-0	0.0
CO (tonnes CO_2 equiv./yr.)	0.0	+0/-0	0.0	+0/-0	0.0	+0/-0	0.0	+0/-0	0.0
N_2O (tonnes CO_2 equiv./yr.)	164.2	NR*	281.6	NR*	+117.4	NR*	281.6	NR*	+117.4
CH_4 (tonnes CO_2 equiv./yr.)	0.0	+0/-0	0.0	+0/-0	0.0	+0/-0	0.0	+0/-0	0.0
Total	**100.1**	**NR***	**27.0**	**NR***	**-73.1**	**NR***	**-135.7**	**NR***	**-235.8**
Total (all parcels)	***100.1***	***NR****	***27.0***	***NR****	***-73.1***	***NR****	***-135.7***	***NR****	***-235.8***

Figure 27. Example of results produced by the COMET Farm Tool

MODULE C: TECHNOLOGY OPTIONS TO SUPPLEMENT SOIL CARBON DATA

This module outlines various technologies that can work with or supplement the more commonly used quantification approaches laid out in modules A and B. In many cases, these are complex technologies that do not lend themselves to simple step-by-step guidance on their implementation, as is done in Modules A and B. Although there is a growing interest of "digitalizing" the MRV process though tokenization and automated data collection and verification, these technologies are more typically applied, at present, in a research environment. With further development and reductions in cost they could be used more routinely in the context of 'carbon projects.' It is expected that recent and upcoming developments in remote sensing techniques and large-scale soil databases will eventually increase monitoring cost-effectiveness, having the potential to facilitate the implementation of soil carbon MRV in the coming years if technical specifications meet project needs. Thus, in this module we seek to introduce the technologies and describe current state-of-the-art and how they might be utilized independently or in conjunction with approaches outlined in Modules A and B, to establish soil organic carbon MRV baselines and collect activity data. The module further provides an assessment of their applicability conditions and discusses relative pros and cons for their application.

The module is structured in three broad types of technologies:

- ***Part A***: Those that are remote sensing-based
- ***Part B***: Those that deploy *in situ* sensors to measure soil carbon
- ***Part C***: Those that install equipment to measure ecosystem carbon flux

Each technology has an associated uncertainty, which should be calculated and presented alongside the soil organic carbon predictions. The uncertainty of the spatial models can be challenging to interpret, yet most remote sensing modeling methodologies have an associated uncertainty calculation protocol that users can follow and apply to their estimates. While large amounts of data can improve prediction and reduce model uncertainty, they also require an extensive understanding of remote sensing and statistical modeling, which may be a barrier for implementation. Advancements in machine learning have led to improved predictions from the models, but these do not improve the uncertainties associated with spectral data or reference data.[7]to enhance resilience to climate change and to underpin food security, through initiatives such as international '4p1000' initiative and the FAO's Global assessment of SOC sequestration potential (GSOCseq Uncertainty of these technologies, their applicability to different assessment purposes, and their expected accuracy are detailed in the sections below.

PART A: REMOTE SENSING TECHNOLOGIES

Remote sensing capabilities (via satellite or airborne platforms) provide a means to collect a diverse set of observations — at regular intervals, over large areas, with low per hectare costs — that can contribute to soil carbon quantification systems. Remote sensing assessments can complement and possibly substitute ground-based measurements, particularly at larger scales and depending on the application. Also, remote sensing data and historical archives of satellite data can provide an assessment of change over time, where reliable historical land or soil surveys are not available. Here we describe three different classes of remote sensing applications that could be part of a soil carbon quantification methodology (Figure 28):

1. direct estimate and mapping of surface soil carbon contents,
2. remote sensing of vegetation attributes or dynamic edaphic conditions (driven by or produced by soils) on the land surface that could be used to drive process-based ecosystem carbon models (see Module B), and
3. remote sensing of management activities that can be used in practice-based carbon inventory systems or can be used as drivers for process-based models (described in Module B).

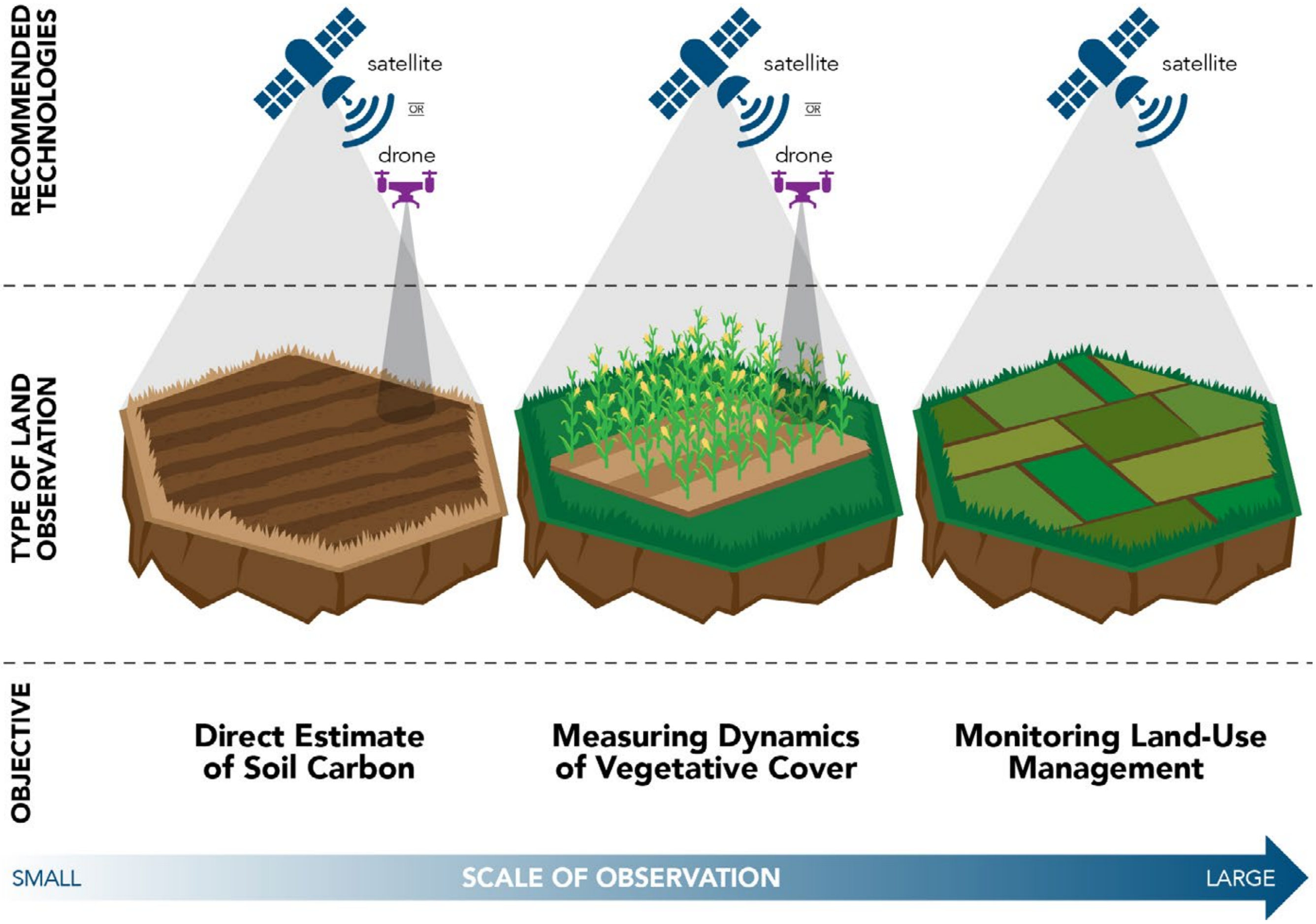


Figure 28. Three different types of Remote Sensing applications that could be incorporated into a soil carbon quantification methodology.

1. Direct estimate of soil carbon

Optical sensors on satellite or airborne platforms have been used to estimate soil carbon concentrations, particularly in annual cropping or grazing systems.[65] The standard technique involves reflectance spectrometry in which the instrument measures the radiation reflected back from the earth's surface, where the wavelengths in reflected radiation are affected by the organic matter content of the soil surface. The visible (300-700nm) and near-infrared (700-2500 nm) wavelengths (Vis-NIR) comprise the regions of the electromagnetic spectrum that have been most frequently used for remote sensing-based estimates of soil carbon concentrations. The basic principles are the same as *in situ* ground-based sensors, explained in Part B of this Module.

Remote sensing-based estimates of soil carbon content often involve building statistical or machine learning models that analyze and correlate observed spectra with ground-based soil measurements.[66–68] Advancements in artificial intelligence and machine learning approaches have led to improved modeling and allowed for analysis of large amounts of data, which can have significant implications for data management and analysis, considering the growing amount of data that is becoming available and the growing capacity to generate it.

Challenges to satellite and airborne spectroscopy include correcting for atmospheric conditions, interference from surface vegetation and/or residue coverage, variations in soil moisture and surface roughness, etc. that influence sensor measurements. Accurate measurements using Vis-NIR ideally require bare soil surfaces, such as under winter fallow conditions in annually cropped soils, and can be reliable for quantifying SOC in the top 1 cm of soil when combined with spectral libraries or multivariate imagery of bare soil patterns.[7]to enhance resilience to climate change and to underpin food security, through initiatives such as international '4p1000' initiative and the FAO's Global assessment of SOC sequestration potential (GSOCseq **Direct measurement of soil organic carbon using remote sensing is best suited for projects that have plots of bare soil**, **and *in situ* sample collection to calibrate the spectral signatures and scale assessment across the project site.**

Scale and Accuracy

Remote sensing models have been shown to accurately and precisely measure soil organic carbon content directly through observations of spectral reflectance.[67,69] These developments have benefitted from advancements in work on atmospheric correction, instrument calibration, the high temporal frequency of observations from space, and machine learning.

- **Satellite observations**: provide broad coverage, with regular return intervals and medium spatial resolution (e.g., 15-30 m). Accuracy is lower than with airborne or UAS (Unmanned Aerial Systems) platforms due to greater atmospheric interference and lower signal-to-noise ratios with satellite observations due to short integration times over target areas.
- **Airborne sensors:** often produce data at high spatial resolution (3-10 m pixels) but require dedicated tasking over limited time frames and come at greater expense. UAS/drone platforms are less expensive, are nearer to the ground, and thus have less atmospheric interference but cover much smaller areas and have limited sensor/payload capacities.

Overall, satellite and airborne platforms have fairly similar performance in terms of accuracy, although there is potential for better results with lower altitude airborne systems as well as higher resolution observations. In contrast, satellite platforms have greater spatial coverage, are much cheaper (for data users), and have regular return intervals over multiyear durations.

There are fewer examples in the literature of low-altitude sensing using drones. However, less atmospheric and vegetation interference, more granular observations and the fact that observations can be more easily staged for a particular field or set of fields when conditions are ideal helps considerably in improving accuracy.

> *Accuracy varies for different studies depending on the ground-surface conditions (e.g., vegetation interference, soil moisture) being surveyed, the conditions (atmospheric interference), the instruments used, calibration data, and data modeling methods employed.*

BOX 3.9 ADVANTAGES AND CHALLENGES OF APPLYING REMOTE SENSING FOR DIRECT SOIL CARBON MEASUREMENT

Advantages

Direct observations via remote sensing to quantify soil carbon contents at present has most utility for improved soil mapping functions and can likely be useful for stratifying land areas in designing ground-based sampling and soil carbon quantification systems. Furthermore, remote sensing allows users to measure soil carbon content beneath the bare soil surface, without dependence on supplementary physical sampling and lab analysis.[135] This has the potential to greatly reduce the cost of soil organic carbon estimation in farmlands and grazing lands.

Challenges

- Analyzing remote sensing data and developing appropriate models and calibrations require specialized skills.
- Spectroscopic observations of soil surfaces only measure near surface conditions (top 1 cm) and are not capable of estimating carbon contents deeper in the profile. This can be overcome by incorporating statistical models of correlation between surface and subsurface soil organic carbon content, but requires specialized skills.
- Accuracy of estimates over relatively small areas and short periods of time is much less than for sampling and laboratory-based analyses and thus the capability to detect moderate changes over time in soil carbon stocks over small areas, for example, as a function of changes in management, is currently limited.
- Reflectance spectroscopy for soil carbon content is optimized for bare soil surfaces and thus the approach is more difficult to implement for soils with permanent vegetation cover or which are largely covered by crop residues, both of which are objectives of regenerative/conservation agriculture and grazing practices. The impact of crop residue on soil reflectance can be reduced using spectral mixture analysis to retrieve the pure soil spectrum[136,137] or using machine learning.[138,139] These factors should be considered when deciding if remote sensing methods are to be used in isolation of or in conjunction with other methods described in this Sourcebook.
- In many regions the bare soil is never visible or the landscapes are too often covered in clouds for this technology to be able to derive the necessary accurate (i.e., high resolution) SOC maps.

Figure 29. Soil carbon stock in an agricultural system depends on carbon inputs and losses. The balance of the two will determine impacts on the existing carbon pool.

2. Measuring drivers of soil carbon dynamics

As mentioned in Box 3.9, vegetated surfaces are a major impediment to direct observation of surface soil organic matter contents which require a bare, (largely) vegetation-free view of the surface. However, sensing of vegetation attributes is, in fact, one of the most prominent applications of remote sensing. Remote sensing has been used extensively to observe the presence or absence of vegetation, the vegetation type (i.e., land cover – forest, grassland, cropland, etc.) and structure (e.g., height), what species are present, the amount of vegetated cover (i.e., leaf area, biomass), the chemical composition of the biomass (e.g., nitrogen content) and even photosynthetic activity.[70–72]

From an ecosystem perspective, soil carbon dynamics are determined by the carbon entering the soil via plants (e.g., biomass allocation to roots, aboveground biomass production, senescence, and surface deposition as litter) minus the loss of soil carbon via outfluxing of CO_2 as a result of decomposition of plant-derived organic matter in the soil (Figure 29). Thus, remote sensing of vegetation attributes can provide a tremendous amount of information about this 'first half' of the soil carbon balance equation (described in Part A of this chapter), namely plant dynamics, when used as part of an ecosystem-level modeling approach.

Soil moisture plays an important role in impacting microbially-driven biogeochemical processes of decomposition and stabilization taking place unseen below the soil surface, which make up the 'second half' of the soil carbon balance equation. Soil moisture can be difficult to predict due to uncertainties in precipitation inputs at field to landscape scales and subsequent dynamics of evapotranspiration, surface evaporation, runoff, drainage, and differential soil water storage capacity. Recent advances in remote sensing techniques to estimate soil moisture thus can inform process-model estimates of soil carbon where soil moisture is a key driver.[73]

For example, data assimilation of satellite-based LAI during the vegetative plant stage in winter wheat reduced the model error for simulation biomass production by up to 50.115 Furthermore, the performance of modeled grain yield predictions improved from 41% with no data assimilation, to 65% with assimilation of LAI and to 76% after assimilation of both LAI and soil moisture measurements derived from Sentinel-1 and Sentinel-2 satellite data.[116]

An example of a remotely sensed vegetation attribute that could be used to drive ecosystem carbon models is leaf area index (LAI) which is typically modeled endogenously as a function of biomass, species attributes, and phenology. LAI is a measure of the canopy exposure to light and thus is directly related to CO_2 sequestration. Observed LAI would account for spatial variability in the vegetation canopy at field to landscape-scales. This is difficult or impossible to capture with models that are only driven by available variables such as gridded temperature and precipitation, typically available at resolutions of a few square kilometers, and land surface attributes from soil maps or digital elevation models that do not capture factors determining fine-scale vegetation patterns.

To date, there are few examples of data assimilation from remote sensing being used in ecosystem-scale carbon models, but given demonstrated improvements from data assimilation in modeling plant productivity at field to landscape to regional scales, it is likely that soil carbon model predictions can also be improved at those scales. Measurements of the drivers of vegetation cover are most relevant for projects with large monocultured fields in which the crop can be monitored overtime to understand the dynamics of the soil carbon sequestration.

Scale and accuracy

The use of remote sensing to improve model-based estimates of soil carbon through data assimilation approaches is most suitable for large field-to-landscape-

BOX 3.10 ADVANTAGES AND CHALLENGES OF THE APPLYING REMOTE SENSING FOR MEASURING DRIVERS OF SOIL CARBON DYNAMICS

Combining data assimilation techniques with simulation modeling remains very much in the research realm at present but offers potential for improved MRV systems in the future. Data assimilation techniques in the realm of ecosystem modeling are largely focused on plant growth modeling. Remote sensing observations of some products, such as LAI estimates, are available. However, there are not widely standardized, available packages for integrating data assimilation processes into models as a routine workflow, and thus modeling specialists would be needed to operationalize a model-based system with data assimilation for a specific application or project. Examples of global soil MRV systems that can be a useful reference to practitioners are available in Annex III. to be able to derive the necessary accurate (i.e., high resolution) SOC maps.

sized projects. Expected improvements in accuracy using data assimilation vs. standard modeling workflows are currently unknown, although improvements in modeling biomass productivity at these scales have been shown to be substantial (see examples above).

3. Monitoring management practice activity

The third area of application of remote sensing to aid in soil carbon measurement and monitoring is through providing **'activity data'** – that is, spatially- and temporally-referenced observations of land use and land management practices that can be used to inform model-based estimation of soil carbon stock changes.

Satellite imagery, in particular from Landsat (since 1972) and MODIS (since 2001), has been used for decades for mapping land use and land cover and changes over time.[74,75]

In annual cropping systems, the use of remote sensing to identify major crops and crop sequences has proved to be relatively accurate under conditions with larger field sizes and crop monocultures such as with large commercial farms (Case Study 3.3). However, the utility of satellite-based remote sensing for mapping crop rotation and cropping system changes over time is much less in small-holder agricultural settings with small field sizes and where multi-species cropping is occurring.

Some land use activities that have a major impact on soil carbon stock changes, such as deforestation and conversion to cropland and pasture, can be mapped quite accurately via remote sensing.123

Case study 3.4: Accuracy of remote sensing in identifying management activities in the US and China

Hyperion hyperspectral imaging at 30 m resolution has been used to map crop types across different regions of the US, with accuracies of 75% to 95% in classifying crop type.[124] Similarly, high accuracy (up to 95%) in crop type classification have been demonstrated using 10 m resolution satellite imagery in north-eastern China.[125]

Other management activities that can be observed via remote sensing approaches include tillage and residue management practices, particularly distinguishing between intensive tillage with complete or nearly complete incorporation of crop residues ("clean tillage") vs no-till or strip-tillage practices which leave nearly all surface residues intact and with minimal soil disturbance.[76,77]

Similarly, presence of out-of-growing season cover crops versus absence of plant cover and bare fallow practices can be monitored via remote sensing.[78] Presence or absence of irrigation can be remotely sensed and in the case of flooded irrigation, for example, with wetland rice cultivation, the duration of flooding and drainage of fields is indicated by standing water above the soil.[79]

Of course, several management practices relevant to soil carbon and GHG management, such as the use of organic amendments and fertilizer applications, cannot be directly observed with remote sensing techniques and thus require ground-based monitoring and/or self-reporting by farmers.

Remote sensing monitoring of management practice activities is most relevant for projects with consistent observable management activities such as tillage or cover cropping over large areas. Small or erratic management activities can be difficult to detect.

Recommendation:

- Even though many aspects of management can be observed remotely, ground-based monitoring of practices should be done on a subset of project areas for verification purposes.

BOX 3.11 ADVANTAGES AND CHALLENGES OF APPLYING REMOTE SENSING FOR MONITORING MANAGEMENT PRACTICE ACTIVITY

Applicability in a carbon monitoring project will be largely governed by the availability of low-cost, pre-processed/classified imagery in the form of spatial data layers. Remote sensing-derived observations for land cover/land use on an annual (or less frequent) time series are available globally with products that can be downloaded for free (**Copernicus Global Land Cover**).[126] In some instances, such as with the crop data layer (CDL) in the United States, 30 m resolution crop type classification maps can be downloaded for free (**USDA Cropland Data Layer**).[127] Where data is free or low-cost, remote sensing observations can complement ground-based observation and provide key inputs to model-based assessments (see Module B).

Most other remote sensing data on practices, such as tillage and residue management, are not generally available and require expertise to process and evaluate the data, although high-resolution data from limited areas (e.g., Central United States) are becoming available for purchase (e.g., **Operational Tillage Information System (OpTIS)**)[128] and it is likely that remote sensing data of use in project-level carbon estimation will become increasingly available in the future.

Scale and Accuracy

A major advantage of using remote sensing for management activity monitoring is the ability to provide estimates at diverse scales. Almost all satellite-based systems are, by definition, global in terms of their coverage. There are, however, broad regional differences in the efficacy of remote sensing, including having fewer cloud-free views in tropical regions (compared to temperate) which interferes with visible and infrared wavelengths that are used for most of the vegetation, residues, and soil sensing.

For observations involving mature plant canopies – i.e., detecting landcover, plant species presence (crop type mapping), and presence or absence of vegetation (e.g., relevant for monitoring cover crop usage) – remote sensing observations can be quite accurate, with upwards of 90% or more accuracy for land cover determination and somewhat less for crop species classification. The latter is practical mostly for commercial-scale monoculture cropping.

Observations of ground-surface conditions such as tillage type, which is typically inferred from surface residue coverage, is lower (with typical ranges of 50-80% accuracy) and is complicated by varied timing of soil preparation activities, local variation soil type, and surface reflectance properties, vegetation interference, less frequent revisit rates of high-moderate spatial resolution sensors, and other factors.[76]

PART B: *IN SITU* GROUND-BASED SENSORS

The time and effort required for sample collection, transport, processing, and laboratory analysis in conventional field sampling are the main contributors to its high cost (see Module A for more information about conventional sample-based approaches). There is therefore great interest in analytical methods and sensor methodologies that can be deployed directly in the field (ground-based), referred to here as *in situ methods*. Some of these can also be applied via remote sensing approaches, described in Part A above.

Diffuse reflectance spectroscopy (DRS) constitutes the dominant approach for *in situ* soil carbon determination, in which visible (400-700 nm), near-infrared (NIR; 700-2500), and mid-infrared (MIR; 2500-25,000 nm) wavelength regions of the electromagnetic spectrum can be utilized.[80] Instruments capable of detecting both the visible and NIR ranges together (i.e., vis-NIR) are often used for *in situ* soil carbon determinations. The general principle for DRS is the same as from satellite-borne sensors used in remote sensing, where different chemical bonds and functional groups within both soil organic and inorganic matter (including water) absorb electromagnetic radiation of different wavelengths. This produces a 'fingerprint' in the reflected energy spectrum, which is a product of the amount and type of organic matter as well other soil properties (e.g., soil texture, water content, carbonate content, clay mineralogy, heavy metals, and other chemical attributes). To convert the measured raw 'fingerprint' spectra to the variables of interest (e.g., soil organic carbon), the spectra are pre-processed and analyzed using a variety of multivariate statistical and/or machine learning modeling approaches to predict observed 'reference' variables (e.g., based on standard laboratory analyses[80,81]).

Recommendation:

- The best results are obtained using locally calibrated models (e.g., field or farm-scale) because these reflect the unique properties of a specific soil type in a local environment, which impact the spectral signature.[82]

The long-term goal is to develop globally applicable spectral libraries[83] that can translate spectral measurements using well-defined measurement protocols and instrument specifications into the variables of interest without requiring (or with minimal) site-specific model calibrations. These could perhaps be subdivided by major soil types and/or geographic regions. These spectral libraries can be used alongside machine learning approaches that are rapidly being developed, to reduce prediction errors. These libraries can also be used in the calibration of laboratory equipment.

These proximal sensor techniques for soil organic carbon content determination both in the field and the lab can allow in the future to make more affordable and accurate measurements than some conventional laboratory measurements (Table 9), supporting the quantitative soil carbon estimates and monitoring at large scales and spatial distributions as long as they can be afforded by the project.[7]to enhance resilience to climate change and to underpin food security, through initiatives such as international '4p1000' initiative and the FAO's Global assessment of SOC sequestration potential (GSOCseq

Table 9. Assessment of proximal sensing technologies in terms of their readiness to underpin carbon accounting methodologies[84]

Method	Features					
	Rapid?	Accurate?*	Cost**	Already developed?	Already in use?	Radioactive source of energy?
Soil organic carbon						
Color	Yes	No	$	Yes	Yes	No
Visible–near-infrared (vis-NIR)	Yes	Yes	$-$$	Yes	Yes	No
Mid-infrared (mid-IR)	Yes	Yes	$$	Yes	-	No
Laser-induced breakdown spectroscopy	Yes	Yes	$$-$$$	Yes	-	No
Inelastic neutron scattering	Yes	Yes	$$$	No	yes	Yes
Soil bulk density						
vis-NIR, mid-IR	Yes	No	$-$$	Yes	Yes	No
Active gamma-ray attenuation - transmission	Yes	Yes	$	Yes	Yes	Yes
Active gamma-ray attenuation - backscatter	Yes	No	$	Yes	Yes	Yes
Gamma- and X-ray computed tomography	No	-	$$$	No	No	Yes

** relative to conventional dry-combustion method for soil organic carbon concentration, and volumetric method for bulk density*
*** Qualitative assessment - $ is low, $$ is medium, $$$ is high.*

Scale and accuracy

The accuracy of DRS methods varies considerably. In general, MIR methods achieve the greatest accuracy but require soil samples to be uniformly dried, homogenized, and finely ground. This would require the same level of soil preparation as for dry combustion laboratory analysis (although with lower cost and higher throughput), such that deployment of MIR has been mainly in the laboratory[85] and not in the field. However, recent studies suggest the potential for field deployment of MIR with new, cheaper portable instruments and ways to correct for variable soil moisture.[86] Currently, vis-NIR methods are generally viewed as more suitable for in-field applications, as it is easier to correct for variable moisture conditions and the instruments themselves are more suitable for field deployment.[85,87] In-field use can include direct scanning of bare soil surfaces, immediate scanning of soil cores taken in the field, or use of sensors configured as field probes[88] that can be inserted into the soil with illumination via fiber optics to measure the reflectance of subsurface soil.

Performance of DRS relative to analysis with modern dry combustion analyzers (considered the analytical gold standard) is difficult to generalize. A summary comparison shown in Table 10 represents a probable best-case scenario, using locally (i.e., field- or farm-specific) calibrated statistical models and research-grade methods and instruments.

Table 10. Summary comparison of the relative accuracy and cost of instrumentation and measurement, based on multiple studies using reflectance spectroscopy;[84] USD refers to cost in US dollars.

Method	Instrument cost (thousands of USD)	Cost per sample (USD)	R^2 (validation)
MIR, dried and ground samples	7-75	6	0.93
Vis-NIR, dried and ground samples	7-75	0.6	0.85
Vis-NIR, field condition	19-68	11	0.81

BOX 3.12 ADVANTAGES AND CHALLENGES OF APPLYING IN SITU SENSORS TO MEASURE SOIL CARBON

Specificity

Raw spectroscopy measurements for soil carbon determinations are passive and non-destructive, and thus can be done more rapidly and cheaper than destructive laboratory analyses. Furthermore, many soil chemical and physical attributes react to these energy spectrum ranges and thus can be measured at the same time. However, that same characteristic also presents the biggest challenge to the use of these methods, in that the signal from different molecular bonds and functional groups can overlap and interfere with each other. Thus, measurements are sensitive to moisture content, soil texture, and other factors that are highly variable in space and time. Because of the specificity of spectral interactions with soil's mineralogy, texture, and organic matter content, among other soil characteristics, spectral fingerprints are not easily generalized. Thus, accurate results would generally require local-scale calibrations. [82]

Novelty

DRS methods are still primarily used in the context of research, and they are yet to be deployed to any significant degree in commercial soil test labs. Similarly, while there are field-deployable vis-NIR systems that are commercially available, they have yet to be used much if at all in existing soil carbon projects. Several other measurement approaches that could be potentially utilized in-field, including laser-induced breakdown spectroscopy[129] and inelastic neutron scattering[130] have been investigated for a number of years but they still remain within the domain of research application and are not deployable for carbon project measurement and accounting.

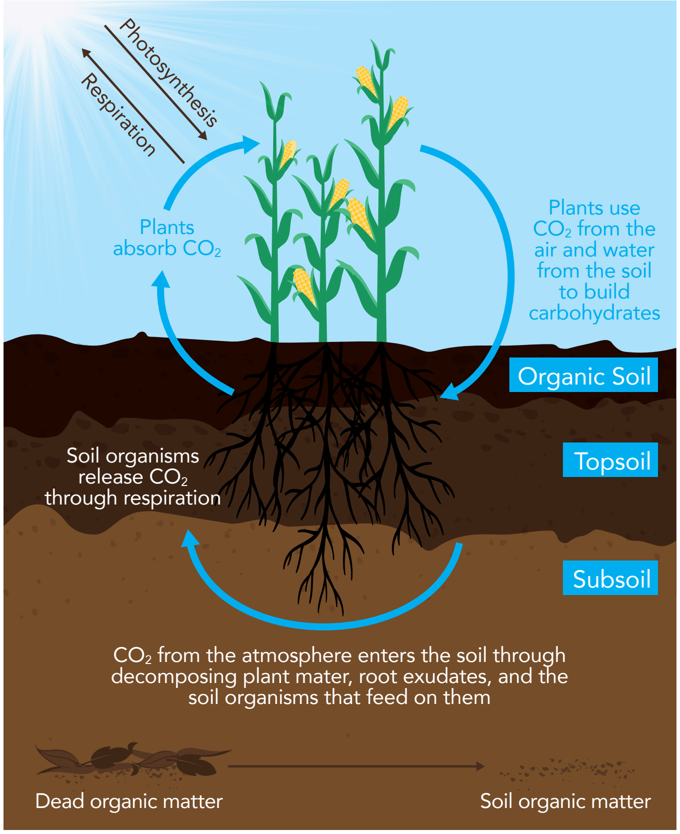


Figure 30. Basics of carbon cycle.
Carbon fluxes shown in blue arrows.

PART C: ECOSYSTEM CARBON FLUX MEASUREMENTS

In most agricultural ecosystems, including annual cropland, hay land, and grazed grasslands, the dominant carbon storage component is soil carbon. In the absence of woody biomass, there is not a long-term accumulation of carbon in aboveground and belowground biomass stocks in these systems and so the net change in total ecosystem carbon stocks is concentrated in the soil.

The overwhelming input of carbon to the soil in most agroecosystems is via the uptake of CO_2 from the atmosphere by plants. Carbon outputs are dominated by plant and soil respiration of previously fixed carbon returned as CO_2 to the atmosphere, as well as the physical removal of carbon in biomass removed as harvested products (see Figure 30). Thus, if the fluxes of CO_2 into and out of the ecosystem can be measured, along with harvest removal, then the net change of carbon stored in soil organic matter can be estimated by a mass balance approach using carbon flux measurements.

The mass balance equation can be summarized as the difference between the carbon gained through storage and the carbon lost through respiration and harvest:

NET ECOSYSTEM CARBON STORAGE = **Plant Carbon Storage** − **Ecosystem Carbon Respiration** − **Harvest Carbon Removal**

This simple mass balance assumes that there are no other carbon inputs (e.g., from manure or compost additions) and that other losses of carbon (e.g., via leaching of dissolved carbon or lateral transport of carbon in eroded soil material) are negligible.

Over the past three decades, instruments, algorithms, and associated data processing to accurately measureCO_2 fluxes between the atmosphere, plants, and soil have been developed and refined. The dominant ground-based technology applied at field scales (and larger) is known as eddy covariance (EC).[89,90] The flux estimates are based on high frequency (i.e., many times per second) measurements of CO_2 concentrations over the plant canopy and simultaneous measurement of 3-D turbulent movement ("eddies") of small 'packets' of air. Thereby, the mean vertical flux of CO_2 between the top of the plant canopy (or ground surface in absence of vegetation) and the atmosphere above the canopy is calculated from the air transport fluxes (measured by a 3-D sonic anemometer, a tool which measures wind speed using sound waves), CO_2 concentration (using an infrared gas analyzer), air pressure, temperature, and humidity.

With fluxes integrated over the year, the measurements capture both the sequestration of CO_2 from the atmosphere into the ecosystem via photosynthesis and assimilation by plants, as well as CO_2 released to the atmosphere from plant and soil respiration. If there are other material transfers to/from the ecosystem (e.g., harvested biomass) they must be accounted for in the system carbon balance. Then, the total net flux (referred to as net ecosystem exchange; NEE) represents the change in carbon storage in the ecosystem.

Scale and accuracy

One of the advantages of EC technology, compared to other on-the-ground flux methods or 'point measurements,' is that they integrate fluxes over a larger area of typically hundreds of square meters within a field and thus 'average out' some spatial variability. Thus, the measurements more closely approximate a 'field-scale' average. The area 'footprint' that the measurements represent is dependent on the height of the sensors. While most implementation of this technology for ecosystem carbon balance investigations are set to represent a subfield-scale area, the technology can be deployed on so-called tall towers to integrate flux measurements over an area of tens to hundreds of hectares, representing more of a mixed landscape measurement. Advancements in instruments and growing numbers of long-term observation studies have reduced uncertainty of EC measurements in recent years.[7]to enhance resilience to climate change and to underpin food security, through initiatives such as international '4p1000' initiative and the FAO's Global assessment of SOC sequestration potential (GSOCseq **As a general rule, the measurement of annual estimates of NEE with EC are likely to be around ± 0.5 to 1 Mg C ha^{-1} yr^{1} or greater.**[91] Thus, by themselves, EC installations in many agricultural settings may not be able to reliably estimate annual carbon sink or source points for some types of management interventions, yet continuous flux measurements are very valuable in improving and calibrating process-based models within a soil carbon quantification system. There are numerous potential sources of error and uncertainty in EC estimates even if all instruments are well-calibrated and functioning properly. Some of the main ones are: Flux estimates are difficult to capture during periods with low air turbulence, which can occur at night.

The technique ideally is applied on flat terrain. In hilly terrain, nighttime lateral air flows (cold air drainage) can cause large underestimates of respiration fluxes that overestimate net ecosystem carbon gains. Furthermore, instrument outages (e.g., from lightning strikes) can cause gaps in the measurement record.

BOX 3.13 ADVANTAGES AND CHALLENGES OF APPLYING EDDY COVARIANCE TECHNOLOGY TO MEASURE ECOSYSTEM CARBON FLUXES

Can be used in any ecosystem with little infrastructure, albeit expensive.

EC approaches have been used in virtually all types of ecosystems, from mature rain forests to semi-desert environments. For agriculture settings in annual cropland and grassland, the infrastructure is not as demanding as in other (e.g., forest) environments. However, the methods still require sophisticated and expensive equipment that requires highly trained personnel to set up and maintain. There are less expensive systems being developed[91] that would allow for field replication with statistical uncertainties, and some companies are offering leasing deals to provide equipment and data processing together in a package. The expense and specialized nature of the instruments are most suited to research-type environments and not for routine deployment in on-farm carbon projects, at present.

Works best in flat landscapes with significant carbon stocks changes.

Optimal installations involve flat, homogenous terrain with easy access and ideally access to grid power, although systems have been deployed in remote locations with solar power and battery backup. EC deployments would be well-suited to situations in which soil carbon stock change rates are relatively high, e.g., conversion of annual cropland to perennial grass or similar land use conversions. For other agricultural systems with more modest changes in management practices, EC systems are most valuable as a complementary method that can be used to improve/constrain model-derived estimates and compare values with estimated stock changes from direct soil measurements.

MODULE D: HOW TO DEVELOP LOOKUP TABLES FOR AGRICULTURAL PRACTICES

Lookup tables provide a pragmatic approach for development projects to cost-effectively track and report soil carbon impacts at scale, avoiding the ongoing need for costly fieldwork or highly skilled consultants. This module answers the following questions:

1. What are look up tables?
2. Why is there a need for lookup tables?
3. How can lookup tables be developed?
4. How can I use a lookup table?

This module targets the development and use of lookup tables that may be used at a smaller, country- or region-specific area for a particular project, rather than global lookup tables.

WHAT ARE LOOKUP TABLES

Lookup tables provide default emission and removal factors that can be applied on an ongoing basis to reported areas under specified agricultural, including grazing, practices. To assess soil carbon under different agricultural practices, these tables would provide estimates for carbon removals and emissions in a range of site conditions on a per unit area basis. Lookup tables should also provide an estimate of uncertainty. An example lookup table is provided in Box 3.14.

A lookup table is usually subdivided into different categories so the estimate can be more targeted to site conditions. The more a lookup table is disaggregated, the more targeted it will be to a project area and agricultural practices implemented in the project area. However, data constraints will always limit the number of subdivisions in a lookup table. Data constraints refer not only to data availability, but to the robustness of the data (i.e., enough results supporting each estimate, or an error number associated with it to understand the accuracy of the values in each subcategory).

Potential subdivisions in a lookup table for soil carbon assessment could include any of the below variables or a combination of any of these:

- Geographic Region/Country/Region within a Country
- Country
- Climatic conditions
- Ecosystem
- Soil type
- Management practice (such as those described in the Introduction chapter)

Once developed based on a combination of field measurement and modeling, lookup tables can be used to estimate:

1. current carbon stocks and
2. projected future carbon stocks following ongoing implementation of climate smart management practices.

BOX 3.14 EXAMPLE LOOKUP TABLE

The table below shows several simplified rows adapted from the lookup table showing sequestration rates calculated using the DeNitrification and DeComposition-Management Factor Tool (DNDC-MFT) model in Canada.131 This lookup table applies only within Canada for a soil depth of 0-20cm over a period of 20 years. Negative values represent carbon removals and positive values represent emissions.

Ecodistrict	Crop rotation	No till (Mg C ha^{-1} yr^{-1})	Eliminated summer fallow (Mg C ha^{-1} yr^{-1})	No fertilizer (Mg C ha^{-1} yr^{-1})	Permanent cover (Mg C ha^{-1} yr^{-1})
Saskatchewan – clay loam	Barley-summer fallow-spring wheat	-0.09	-0.26	0.13	-0.71
	Peas-corn-summer fallow	-0.10	-0.21	0.14	-0.71
	Spring wheat-summer fallow-peas	-0.10	-0.2	0.12	-0.72
Saskatchewan – loamy sand	Barley-summer fallow-spring wheat	-0.03	-0.16	0.13	-0.36
	Peas-corn-summer fallow	-0.02	-0.2	0.12	-0.38
	Spring wheat-summer fallow-peas	-0.03	-0.19	0.10	-0.39

Defaults provided on a per hectare basis

Defaults are split between different regions, soil types, and key crop types

No error is provided – it is recommended to always provide estimates of variability with lookup values

Different management practices have different defaults

Why are lookup tables needed

Ongoing field measurement or modeling is limited by cost, accessibility, resources, or time constraints. In these cases, lookup tables allow anyone to generate estimates of removals or emissions using just the lookup table defaults and management area.

Lookup tables provide a low-cost, simple solution to estimate removals and emissions.

Using lookup tables to estimate emissions and removals is:

- **Low-cost**: it does not require ongoing field visits, equipment, laboratory processing fees, or intensive training.
- **Fast**: it can quickly be done knowing just a few project site characteristics.
- **Simple**: after initial development, it does not require field sampling nor require complex modeling.
- **Consistent:** using the same defaults ensures comparability across projects, sites, or time periods if a project is expanded – as long as the area is reported each year, programs could be expanded almost endlessly, and lookup tables could consistently generate an estimate.
- **Useful:** they are a step beyond currently available IPCC defaults, which can be either not reflecting up to date carbon estimates and rates of change, too coarse to reflect activities implemented and/or monitored by the project, or not applicable to project activities.

For projects without time and resources to invest in ongoing carbon accounting, lookup tables are therefore an attractive solution even though they may not be as precise or accurate as site-specific ongoing field measurements or modeling for local conditions.

Existing international soil carbon lookup tables

IPCC Guidelines: The 2006 IPCC Guidelines present widely used methodologies to calculate emissions and removals from land use change.[1] Such numbers are globally applicable but provide little specificity by agricultural practice or climate. As such, these look up values are unlikely to be sufficient except in situations where only a broad indication is needed of soil carbon impacts.

Empirical Models: There are several examples of empirical 'calculators' which use the IPCC model to calculate the impacts of land use change on soil organic carbon (see Module B). In many of these, users can see the default values provided by the IPCC and used in the calculations. These include reference values of soil organic carbon content under native vegetation and factor values for how different management practices will impact soil carbon stock. Many calculators also provide a measure of the uncertainty associated with the value, which is often very large as the factors can be generalized for large areas. Being able to see the values used in the calculators allows users to compare the value being used to local data, if available. Many of these calculators also allow users to replace the default values from IPCC lookup tables with their own data, which can reduce uncertainty and make the estimate more site-specific. The Carbon Benefits Project (CBP) calculator, for example, encourages users to upload their own project-specific values to the CBP's own look up table, which is then accessible to other users. For more information, see Module B. These empirical models can effectively be used as lookup tables as described in this module. The accuracy of outputs will be less than those from field measurement or process-based modeling but will provide low-cost and defensible data where the circumstances do not require higher accuracy (see Chapter 2). Users are encouraged to enter project-specific data wherever possible to enhance the quality of the outputs.

Additional databases that can be used as lookup tables on a local scale are available in Annex III of this Sourcebook. The section below describes how to use these and other resources to develop lookup tables.

HOW TO DEVELOP A LOOKUP TABLE

Although using a lookup table is simple, developing a lookup table requires time and resources and can be divided into the following steps.

Step 1: Review existing tables

1 REVIEW EXISTING TABLES
2 CHOOSE METHODOLOGY
3 DECIDE ASSUMPTIONS
4 COMPILE LOOKUP TABLE
5 PROVIDE UNCERTAINTY

There may be circumstances where lookup values already exist. The first step should therefore be to conduct a literature review of (1) published literature, (2) government data and methodologies, and (3) grey literature to determine whether a lookup table already exists in the given region. National Inventories and emissions reporting may provide Tier 2 and Tier 3 emission factors and are a good place to start. Long-term field studies could also be applicable, as could modeling of soil changes within the country or project region.

In this case, careful effort should be put in to ensure the lookup values are appropriate to the site and the agricultural management practices being implemented. Indicators of higher quality literature data could include:

a) data from peer-reviewed journal,
b) data from official government sources,
c) methodology clearly described and following procedures listed in Modules A and B,
d) uncertainty provided with estimates.

Step 2: Choose methodology

1 REVIEW EXISTING TABLES
2 CHOOSE METHODOLOGY
3 DECIDE ASSUMPTIONS
4 COMPILE LOOKUP TABLE
5 PROVIDE UNCERTAINTY

Lookup tables are most cost-effectively developed using process-based modeling (see Module B), often paired with limited field measurement (see Module A of this Sourcebook for field measurement options).

Under a modeling approach, a model is used to define soil organic carbon removal and emission rates under different management practices, in different soil types, or under different climactic conditions. This will likely rely on some initial field measurements to define starting stocks (see Module A of this Sourcebook). Alternatively, literature values could be used to determine initial stocks where literature can be shown to be representative of the project sites. Other simple measurements (such as pH and soil type) may be required for the model and could be assessed at the project site.

On a larger scale (such as continental or global), it could also be appropriate to develop a lookup table based on a literature review rather than modeling. However, this is likely not relevant at a smaller, project-specific level given the limited studies available and is therefore not discussed in this approach.

Case study 3.5: Development of a look-up table

The California Department of Food and Agriculture (CDFA) developed a lookup table of soil carbon gains and other GHG emissions for areas undergoing whole orchard recycling (WOR) in different counties in California as part of their Healthy Soils Program Incentives Program.[132] The CDFA validated the DNDC model against field data and then used it to develop county-specific estimates based on local climate, soil, and orchard management conditions. The emission factors from these lookup tables are then used in the reporting and verification processes for Californian WOR projects.[132]

Step 3: Decide assumptions

Because lookup tables are a simplification of what emissions and removals would really be, they rely on certain assumptions. These should be clearly addressed by answering the following questions:

1. ***What are the desired output figures?***
   In this case, desired outputs should be the **annual change in soil stocks** as a result of a particular management practice in a certain region.

   > ***Recommendation*:**
   >
   > - Changes should be reported at a standard depth (most often, the top 30cm).

2. ***How will the lookup table be subdivided?***
   Priority categories should be defined. There will likely be different look up tables for different sets of agricultural practices being implemented. Equally, where there are markedly different climates or soils, there should be differentiation.

3. ***How will the lookup table account for changes in rates over time?***
   The model will define the period over which changes in soil organic carbon will occur prior to reaching a new equilibrium. The look up table may have numbers that vary by year or may be linear from starting stock to the estimated equilibrium value. Many models show that rates of change may be highest at the beginning stages of the project and reduce in later years.

4. ***How will the table account for the combination of multiple management practices?***
   As outlined in the introduction, agricultural practices impact SOC in different ways and may have different impacts when combined with each other. It will be necessary to select one or a small number of combinations of practices that will be implemented as part of the project. This combination of practices will be the basis of the modeling and will derive the lookup values for users to extract in the lookup table.

Step 4: Compile lookup table

The modeled data should be compiled into a lookup table of defaults, following the categories and subcategories selected and the assumptions made in the previous step. It is recommended to compile the lookup table using consistent subdivisions of each category (see example in Box 3.14), for comparability of defaults. If one of the cells in the table does not have enough data available to develop a default, it should be noted in the table.

Step 5: Provide uncertainty

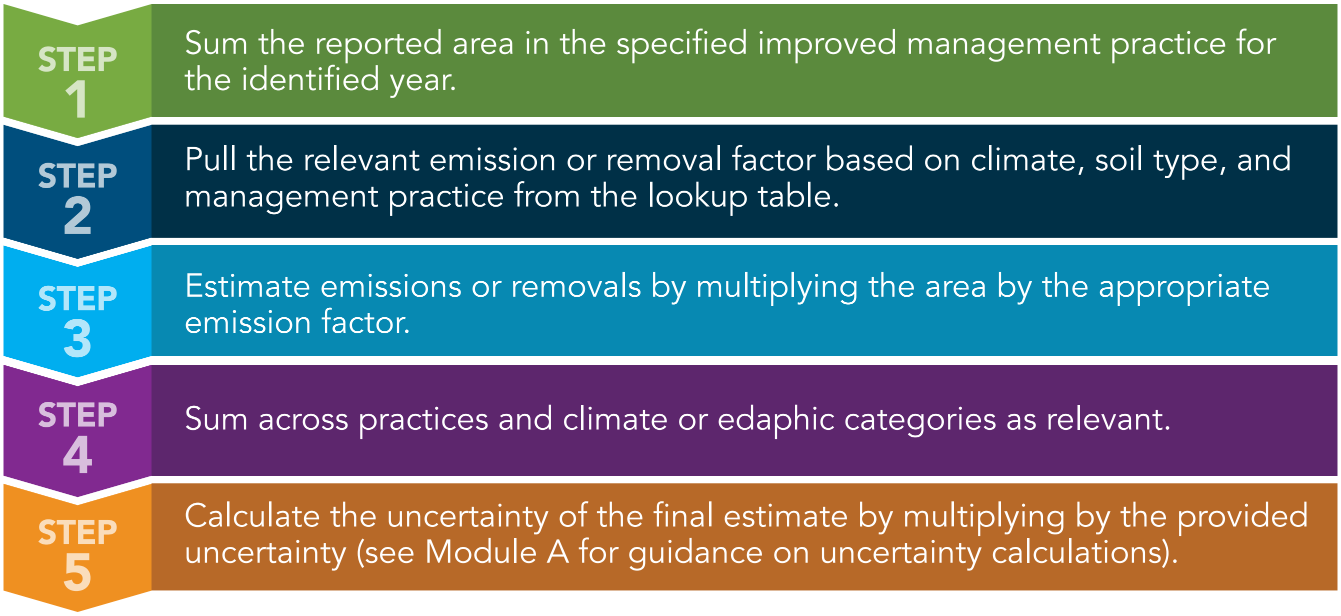
1 REVIEW EXISTING TABLES
2 CHOOSE METHODOLOGY
3 DECIDE ASSUMPTIONS
4 COMPILE LOOKUP TABLE
5 PROVIDE UNCERTAINTY

An associated uncertainty should be reported with each default, as it represents just an estimate of the true value. The associated uncertainty will be driven by both sampling and analysis errors, particularly any inherent errors in the chosen model and errors in values pulled from the literature. Error is typically presented as half the confidence interval as a percentage of the mean, as explained in Module A. Simple error propagation may be needed to combine uncertainties when category defaults are comprised of multiple values from independent analyses. Box 3.3 in Module A explains how this can be calculated.

Defaults may inherently have high uncertainty, especially in certain countries, because they are derived from broader averages which may focus more on some regions than others. Developing region-specific or country-specific emission factors helps to reduce bias in default emission and removal factors.

HOW TO USE A LOOKUP TABLE

The steps to use lookup tables are detailed in Figure 31, and an example of the steps below can be found in Box 3.15.



STEP 1 Sum the reported area in the specified improved management practice for the identified year.

STEP 2 Pull the relevant emission or removal factor based on climate, soil type, and management practice from the lookup table.

STEP 3 Estimate emissions or removals by multiplying the area by the appropriate emission factor.

STEP 4 Sum across practices and climate or edaphic categories as relevant.

STEP 5 Calculate the uncertainty of the final estimate by multiplying by the provided uncertainty (see Module A for guidance on uncertainty calculations).

Figure 31. Steps to use a lookup table for soil carbon assessments in for agricultural practices.

BOX 3.15 EXAMPLE CALCULATION

This example relies on the example default values provided in Box 3.14.

STEP 1: There are **10,000 ha** of cropland in Saskatchewamn with clay loam soils under a rotation of Peas-corn-summer fallow and with no tillage. There are another **20,000 ha** in Saskatchewan with loamy sand soils under a Spring wheat-summer fallow-peas rotation and with no tillage.

STEP 2: The appropriate emission factors from the lookup table for the specified regions in Step 1 are **-0.10 Mg C ha^{-1} yr^{-1}** and **-0.03 Mg C ha^{-1} yr^{-1}**

STEP 3: 10,000 ha x -0.10 Mg C ha^{-1} yr^{-1} = **-1,000 Mg C yr^{-1}** and 20,000ha x -0.03 Mg C ha^{-1} yr^{-1} = -**600 Mg C yr^{-1}**

STEP 4: -1,000 Mg C ha^{-1} yr^{-1} + -600 Mg C ha^{-1} yr^{-1} = **-1,600 Mg C ha^{-1} yr^{-1} would be sequestered in this system.** Over 20 years, this would be equivalent to **32,000 Mg C**.

STEP 5: There is no uncertainty provided in this example lookup table.

CHAPTER 4: PUTTING THE GUIDANCE OF THIS SOURCEBOOK INTO PRACTICE

Building on Chapters 1 through 3, this chapter provides a brief overview of key messages provided by this Sourcebook, and next steps on how to apply this guidance on soil carbon measurement and monitoring assessments.

IMPLEMENTING THE GUIDANCE OF THIS SOURCEBOOK

Croplands and grazing lands play a key role in global carbon cycles because of their massive extent, significant soil organic carbon stocks, and frequent state of intensive environmental pressure due to degradation or unsustainable management. It is essential that projects that intend to conserve soil carbon, increase soil carbon sequestration, and/or reduce soil carbon emissions in agricultural settings integrate both a climate change and a food security perspective into land management, as low soil carbon can reduce crop and grazing land productivity.

To this end, this Sourcebook provides guidance to understand better how much carbon is stored in soils and how soil carbon storage changes with management practices, the first step towards making informed decisions on improving soil carbon stocks and reducing agricultural soil degradation. Assessment and monitoring of carbon benefits generated by a carbon project can be integrated with national approaches (such as NDCs and national GHG inventories), allowing for a more cohesive and cost-effective implementation of agricultural land management strategies and potentially increasing the robustness of both activity data collection and emission factor development. The potential impact of cropland and grazing management practices on soil carbon and potential project financing options are described in Chapter 1 of this Sourcebook, with guided next steps on decision-making in Chapter 2 that link the reader with specific methodological guidance in Chapter 3 Modules depending on the most suitable and cost-effective approach to measure and monitor soil carbon and soil carbon changes over time.

Practices that increase soil carbon inputs

NUTRIENT MANAGEMENT

- Integrated use of chemical fertilizers
- Compost/manure
- Crop residues/mulch
- Biochar

VEGETATION COVER MANAGEMENT

- Crop rotation
- Cover crops
- Managed fire
- Mixed cultivation, agroforestry

Practices that decrease/avoid soil carbon losses

WATER MANAGEMENT

- Reducing evaporation
- Reducing runoff
- Irrigation

TILLAGE MANAGEMENT

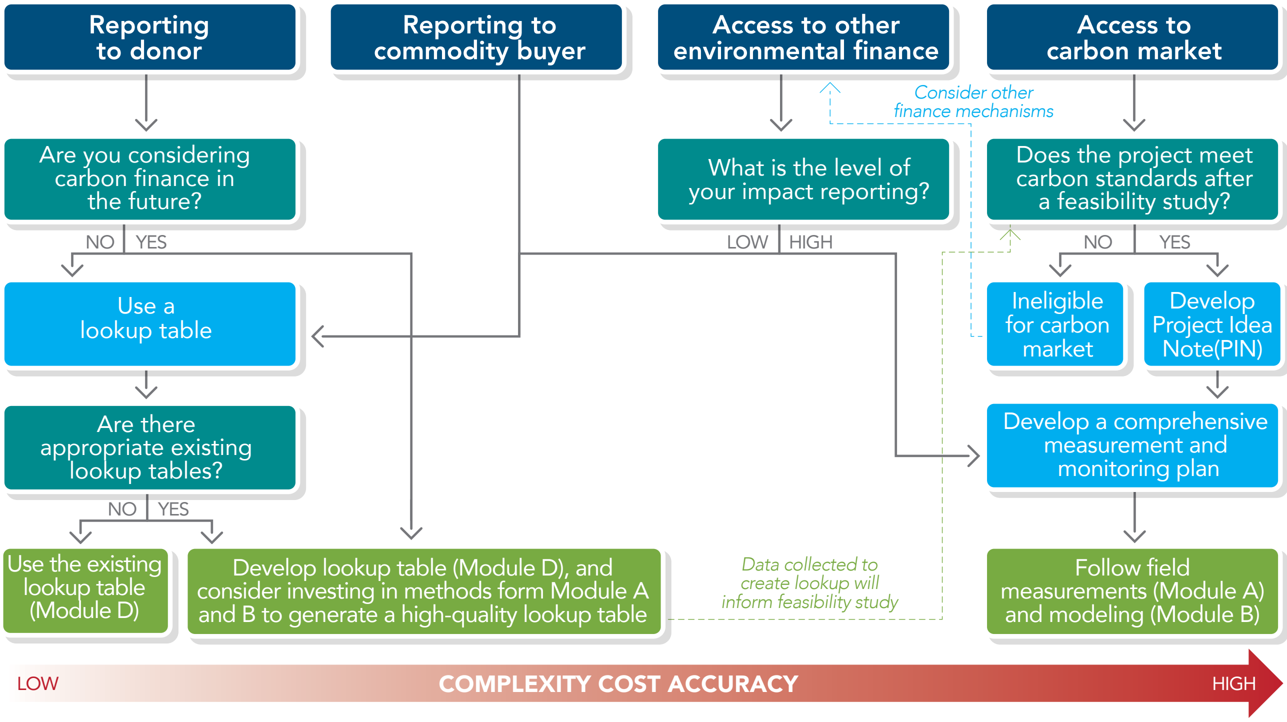
- No-till
- Reduced till

GRAZING MANAGEMENT

- Rotational grazing, regenerative grazing
- Reduction of livestock grazing hours

CHOOSING A SOIL CARBON ASSESSMENT APPROACH

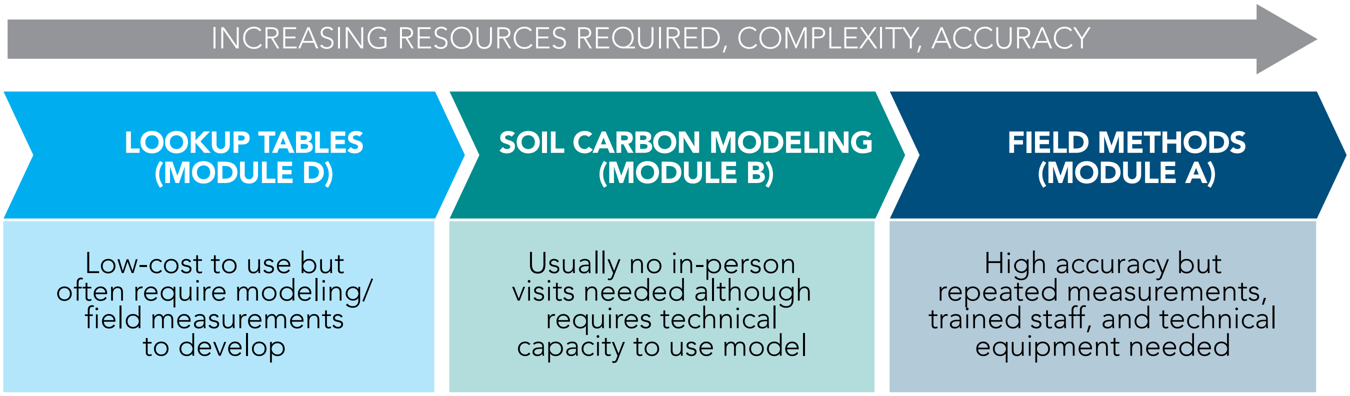
This Sourcebook stresses the importance of choosing a soil carbon assessment that fits the purpose of the assessment, the resources available for investment in monitoring, and the likelihood that the purpose of the assessment will evolve in the future. The decision tree below and described in detail in Chapter 2 shows how the purpose of a soil carbon assessment can be categorized into four broad groupings based on the required level of accuracy in assessing soil organic carbon going from basic (i.e., reporting to a donor) to high-end (i.e., carbon certification) performance-based carbon assessment and monitoring. Reporting to national commitments, for example NDCs, would follow simplified reporting, although typically would require direct adoption of the approaches used in the national inventory.



Despite the different levels of accuracy of these options and thus the uncertainty associated with the soil carbon estimates they generate, all data, methods, and calculations need to meet the required level of quality and detail laid out by the carbon finance or reporting framework followed. In any case, **assessments should be aligned at minimum with the requirements set forth by the IPCC Guidelines.**

The proposed options for soil carbon assessment and monitoring can be implemented as standalone approaches or combined to meet project needs and carbon monitoring requirements cost-effectively over time. Depending on these needs and requirements, a combination of non-field and field methods will be required. Soil carbon accounting and monitoring are typically designed to collect and report information on project activities that can be tracked through surveys and statistics or remote sensing. To accurately assess this carbon impact, models (and especially process-based models) must be previously validated for the target region (most often with field measurement) to verify assessments and adjust models as needed. In this context, the use of lookup tables has been particularly successful for soil carbon MRV at scale.

Lookup tables (Module D) would rely on data generated through modeling (Module B), field measurements (Module A), technology (Module C), and literature or database review to develop new lookup tables useful for the project to assess soil carbon and monitor its potential changes over time. For a full description and guidance on how to implement these methods, we refer the reader to the specific modules in Chapter 3, and in particular to the step-by-step guidance, recommendation boxes, and implementation examples provided in them.



LOOKING FOR MORE IN-DEPTH INFORMATION

The Sourcebook Annexes provide more in-depth information on how to develop soil carbon assessments that meet the most rigorous reporting requirements of carbon markets, with useful step-by-step guidance, examples, and key concepts to understand.

The Annexes include a list of useful resources for projects and implementers of sustainable agricultural management practices that seek to conserve or increase net soil carbon gains. These resources include descriptions and links to existing soil carbon monitoring initiatives and monitoring systems, publicly available datasets to assess both project activities and soil parameters that are widely used for field assessments and soil carbon modeling and that can help in the development of lookup tables, a list of agencies and standard carbon assessment methodologies for cropland and grazing land assessments, and a list of practical examples from World Bank projects in agricultural settings.

Crop production and grazing and the soils on which crop production and grazing are conducted have incredible potential to either positively or negatively impact the atmosphere and our current climate crisis. The lack of cost-effective methods and capacity to implement these methods should not be barrier to the participation of agriculture. This Sourcebook seeks to contribute to democratizing the knowledge and resources necessary for agriculture to play the most positive role possible in climate change mitigation.

ANNEXES

These annexes provide additional information to the chapters and include:

- *Carbon market guidance*
- *Key carbon market concepts*
- *Resources, including agencies and initiatives, standard methods, and databases*
- *Case studies*
- *Glossary of terms*

ANNEX I: CARBON MARKET GUIDANCE

For agricultural soil carbon projects that seek to participate in the carbon market, there are a set of steps that must be undertaken as well as a set of concepts that must be understood with associated analyses. This annex provides information and guidance for users with examples derived from successfully implemented projects.

STEPS TO DEVELOP A CARBON CREDIT GENERATING PROJECT

The steps to develop a project to generate carbon credits for the voluntary market are explained in detail below (and summarized in Annex Figure 32). These steps are complementary to the information provided in Module A of this Sourcebook about designing soil carbon assessments in agricultural settings, as a carbon credit generating project involves all of the steps described in Module A but tailored to a greater level of accuracy to meet the requirements of carbon standards.

Annex Figure 32. Flow chart of the steps to develop a project to generate carbon credits for the voluntary market.

ANNEX BOX 1 DEFINING PROJECT BOUNDARIES

Geographic boundary: A Project may contain more than one discrete area of land, but each must have a unique geographical identification and each land area must meet the applicable sector-specific land eligibility requirements. The project designers should also consider the leakage potential and social environmental impact of the project activity and adjust the boundary accordingly.

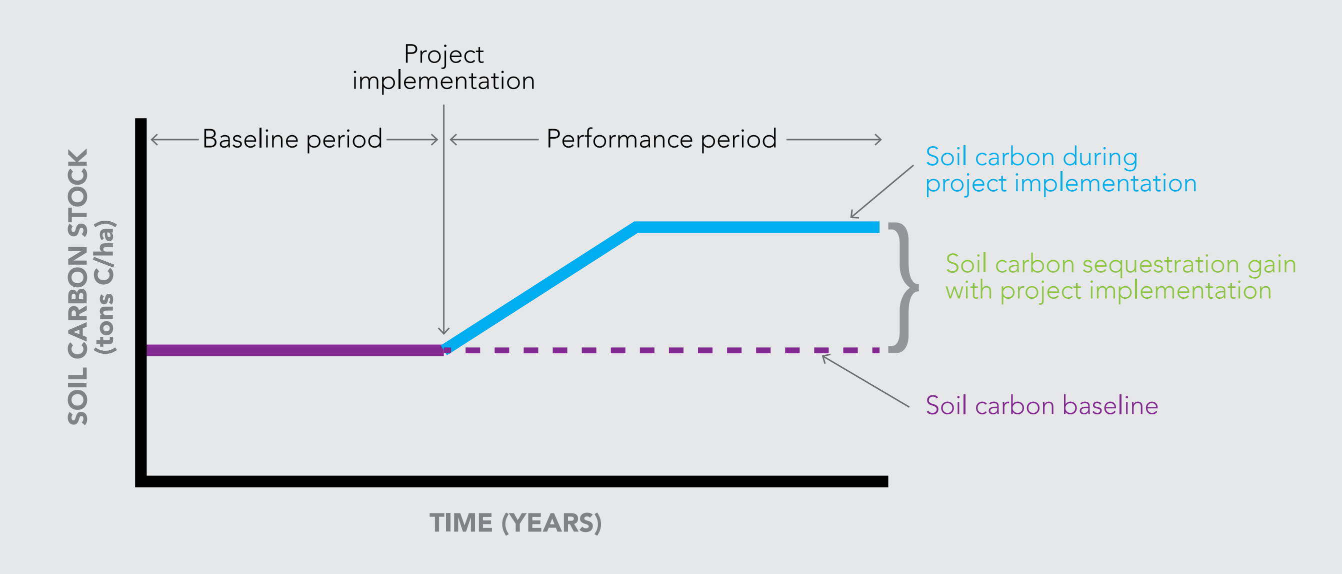
Accounting boundary: A project must detail the carbon pools (e.g., SOC), and gases included (e.g., carbon dioxide, methane, and nitrous oxide). If a pool or gas is omitted, it is necessary to provide a justification demonstrating that the omission is either of very low significance to total emissions/removals or is conservative with regard to the calculation of greenhouse gases released into the atmosphere.

The first step of a carbon project is to define the project boundaries which, in the carbon project context refer to the geographical boundaries, the planned project activities, and the baseline scenario. Furthermore, soil carbon assessments in agricultural settings would have direct emissions (i.e., changes in soil carbon, non-CO_2 soil emissions from nutrient amendments) or emissions from direct consumption of fuel or electricity to manage the agroecosystem (e.g., fuel to run farm machinery). This SOC Sourcebook, however, focuses on changes in soil carbon in agricultural lands that are a direct consequence of land management and only considers the soil carbon pool. The timeframe to develop and implement a carbon project, depends on the project proponent, and on specific details such as whether there are any land tenure conflicts and/or the potential need to get approval from the jurisdictional or national government.

Define Project Activities and Baseline Scenario

The carbon project needs to define the activity that will be implemented during the project, and clearly identify the management practices that would be (or are) implemented in the project boundaries in the absence of the project that constitute the **project baseline**. The logic behind a carbon project is that implemented project activities generate carbon benefits, or carbon credits, through demonstrating a higher soil carbon stock in the with-project scenario than would have occurred in the absence of the project either through more sequestration or fewer emissions.

The baseline is the 'business as usual' scenario, against which changes in carbon stocks are monitored over time, and carbon gains, or "offsets", are generated (Annex Figure 33). Defining a carbon baseline is therefore a fundamental step when developing projects for carbon financing.



Annex Figure 33. Conceptual representation of soil carbon stock increase over time compared to the baseline scenario, generating sequestration gains with project implementation.

In most cases, the baseline will be a continuation of the agricultural land management already occurring on the land (Annex Figure 33), and likely the soil carbon stocks will be already at a stable level. The project will then implement sustainable or conservation agricultural practices that will be expected to increase carbon stocks in the soil.

For example, the baseline may be low yield agriculture on highly degraded soils. The project activity could include application of organic fertilizers (e.g., manure), use of cover crops and growth of trees of field boundaries. All the carbon sequestration in the soils as a result of these activities are a net gain for the project and can result in carbon credits.

More complex scenarios can exist. For example, the baseline may include shifting cultivation, or could include land recently converted from grassland. In these cases, the baseline will include a loss in soil carbon as soil degradation continues to a new stable point. In this situation the baseline would have to be modeled, or be measured on proxy sites.

Baseline periods should be multi-year and representative of reference conditions. The performance period, on the other hand, is defined by the period in which effective changes in soil carbon stocks would be expected and measurable over time. The voluntary carbon standards have specific requirements about the length of baseline and performance periods that should be followed if the project seeks to generate carbon benefits tradeable under the registry of the standard.

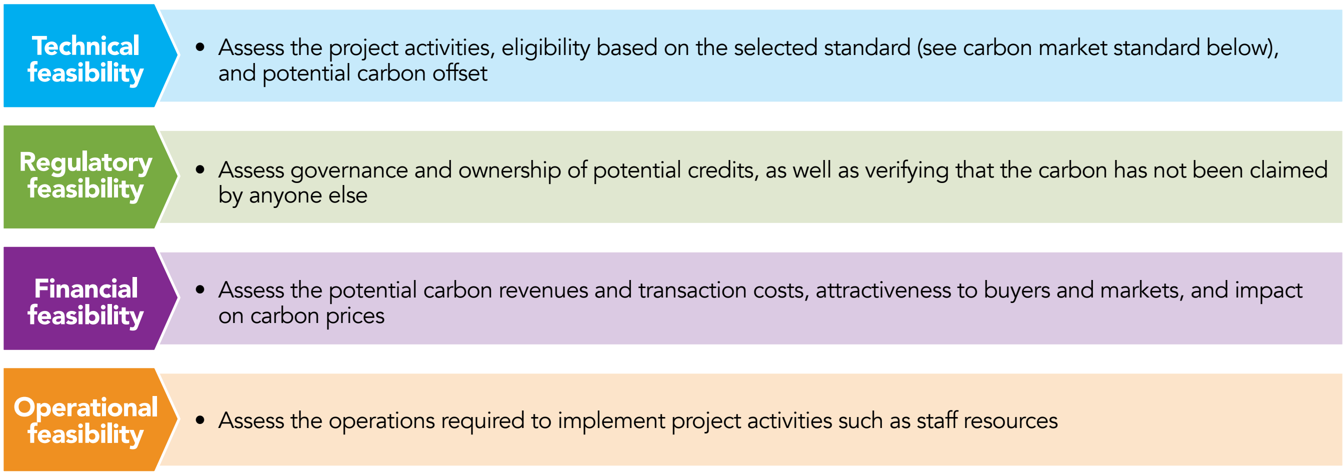
STEP 2 Conduct a feasibility analysis and select a carbon market standard

When a project to generate carbon offsets is developed, an initial assessment of the potential carbon gains a project could achieve and the socioeconomic and environmental feasibility of the project is required. The **feasibility study** must assess whether the project would be eligible to eventually produce potentially saleable emission reductions (i.e., carbon credits). A feasibility assessment should analyze *how* and *if* a project can generate carbon credits, and the best carbon market standards to select.

Projects should be refined and even redesigned through the process of the feasibility assessment. The feasibility study addresses the technical, regulatory, financial, and operational feasibility of the carbon project (Annex Figure 34). The feasibility analysis is often concluded in the form of a Project Idea Note (PIN) which is documentation that can be used in fundraising for the project start-up or for getting offset purchasing commitments.

ANNEX BOX 2 KEY QUESTIONS WHEN ASSESSING THE FEASIBILITY

- Have the legal rights to the carbon credits been secured?
- Does my project have low displacement (leakage) potential?
- How do the costs required to secure the carbon compare with the potential income from credits?
- What is the risk of my project failing or not generating the expected carbon benefits?
- Does my project minimize negative environmental and socioeconomic impacts?



- Assess the project activities, eligibility based on the selected standard (see carbon market standard below), and potential carbon offset

- Assess governance and ownership of potential credits, as well as verifying that the carbon has not been claimed by anyone else

- Assess the potential carbon revenues and transaction costs, attractiveness to buyers and markets, and impact on carbon prices

- Assess the operations required to implement project activities such as staff resources

Annex Figure 34. Flow chart of the steps to produce soil carbon assessments.

It is also important to consider and address the barriers which may limit success. Successful adoption of projects that intend to generate carbon credits through the enhancement of soil carbon sequestration requires overcoming potential economic, institutional, and legal barriers that can be particularly significant for smallholders.[26,29,92] The main barriers are described in Annex Table 11.

Annex Table 11. Barriers to successful adoption of carbon credit generating projects.[26,29,92]

Adoption barrier	Explanation	Options to overcome
Economic: Delayed return on investment	Implementation of SOC-sequestering activities undergoes a transition phase until a new SOC equilibrium is reached. Generating SOC benefits over this transition can take several years. If the adoption of the SOC-sequestering activity requires an upfront investment or entails a temporary reduction in land productivity, the economic strains can be a major barrier for adoption.	PES with credit programs, subsidies, or upfront payments can enable overcoming initial investment barriers. Collective engagement can help reduce transaction costs. The transition phase can maintain or increase income through improved markets (when change decreases productivity) or alternative income sources from other farm products.
Institutional: Collective action challenges	When implementation is intended at the landscape level, engagement and coordination of farm owners would be required. This can be particularly challenging in fragmented landscapes with multiple stakeholders.	Community organization through cooperatives or institutional support and coordination can facilitate engagement and collaboration between farm holders, and build capacity for diversified, efficient, and sustainable land management.
Legal: Lack of tenure security	Unsecure tenure threatens the long-term maintenance of implemented SOC sequestering activities and thus the generation of SOC benefits. The rights to SOC increases need to be clearly defined to receive payments for them. Farmers with irregular tenure are unlikely to participate due to benefit uncertainty.	Addressing any tenure issues during the design of the PES agreement can help guarantee the generation of SOC benefits and fair compensations for them. On occasion, PES agreements have helped formalize irregular or conflictive tenure (e.g., Costa Rica).

Selecting a carbon market standard

As a part of the feasibility study, the project must assess and ultimately select the carbon market standard and associated methodology to pursue based on project details, objective, and eligibility. Most standards cover similar activities related to agricultural soils, including tillage, manure, and compost management, or changes to cropping or grazing cycles. However, it is critical to confirm the chosen Standard would both be attractive to potential buyers and will allow the specific activities and accounting approach you are proposing. Eligibility requirements include criteria related to the historical land use transitions within the project boundary, and the impact of the project activity. Each standard outlines the measurement and modeling requirements, and some may even require a specific model. A brief overview of possible carbon market standards related to SOC is included in Annex Table 12.

Annex Table 12. Relevant voluntary market carbon standards and approved methodologies for soil carbon projects in agricultural settings.

Standard	Key Eligibility Conditions	Eligible Project Activities	Soil carbon accounting method
Verified Carbon Standard (VCS/ VERRA)	**Adoption of Sustainable Agricultural Land Management (VM0017):** The area must be cropland or grassland at the start of the project, wetlands are not applicable. The area of land under cultivation in the region must be constant or increasing.	Any activity that increases the carbon stocks, manure management, cover crops, crop residues, and introducing trees to the landscape.	Direct measurement or modeling.
	Methodology for the Adoption of Sustainable Grasslands through Adjustments of Fire and Grazing (VM0032): The project area must be grassland before project activity.	Livestock grazing and/or grouping, timing, and season of grazing in ways that sequester soil carbon and/or reduce methane emissions or altering fire frequency and/or intensity.	Direct measurement or modeling.
	Improved agriculture management (VM0042): A project must not involve a change in land use before and after project implementation. The standard covers the secession of a pre-existing practice, adjustment of preexisting practice to increase GHG removals.	Reduction in fertilizer, improved irrigation, reduce tillage/improve residue management, improve crop planting and harvesting, or improved grazing practices.	Measured and modeled. Where models are unavailable or have not been validated, an additional approach to measure and remeasure is available.
Plan Vivo	The project activity areas have not been negatively altered prior to the start of the project to increase climate benefits. Soils in the project area are not waterlogged and at least 30-cm deep.	Conservation Agriculture, tree planting, and agroforestry.	Direct measurement or modeling. SHAMBA tool to model the baseline.[93]
Gold Standard	The project area cannot be a wetland or forest. No biomass burning. The project areas must have been a cropping system for the last 5 years and not resulted in any land use change. Eligibility is also contingent on maintaining food security so there can be no reduction (based on a 5-year average) of crop yield due to the project activity.	Changes in agricultural practices.	Direct measurement or modeling, peer-reviewed publication on Tier 1/2.

STEP 3

Develop the project design document (PDD) and submit to the standard

Each standard has specific documentation required which must be developed, submitted, and maintained over the life of the project. A Project Design Document (PDD) describes the project characteristics, and monitoring plan according to standard methodologies, and includes calculation of baseline emissions and estimations of project emission reductions. The PDD must clearly address the following project characteristics according to the criteria outlined in the standard:

1. **Project eligibility:** A project must demonstrate it meets the eligibility requirements of the selected standard and methodology.
2. **Baseline and *ex-ante* estimations**: A project must implore the methodology detailed in the standard to calculate the baseline, the emission expected in the absence of the project, and the ex-ante estimations (future forecasting).
3. **Additionality:** A project must demonstrate the carbon sequestered is additional to what would have occurred in the absence of carbon finance. See Annex II for more details about how additionality is defined.
4. **Leakage**: Implementation of carbon-sequestering activities in the project area might lead to displacing carbon-emitting activities outside of the project boundaries, effectively reducing the net benefits of the project. A project must be designed such that it addresses any potential leakage of emissions outside of the project boundaries. See Annex Box 3 and Annex II for more details.
5. **Permanence:** Projects must provide an estimate of the time carbon will be sequestered under the project activities. Most standards will include guidance that can be used to model the permanence of carbon sequestration. See Box 4 and Annex II for more details.

The PDD containing all components described in Annex Figure 35 should be submitted for validation. Once approved, project implementation will have to follow the parameters outlined in the PDD.

- **Monitoring Plan: as outlined in standard methodology**
- **Stakeholder comments**
- **Social and Envionmental Assessment**
- **Assessment of permanance and risk.**
- **Leakage avoidance plan**
- **Calcualtion of baseline and ex ante estimation of emission reduction**
- **Demonstrate additionality**
- **General description of the project activity**

Annex Figure 35. Components of the Project Design Document (PDD) to submit to the carbon standard for validation.

ANNEX BOX 3 LEAKAGE

Carbon projects must conduct full project leakage accounting.

Leakage can be caused by:

- Activity shifting, e.g., a project activity to leave a field fallow with a cover crop and might result in farmers converting a new parcel of land from forest to crop field resulting in more emissions to the atmosphere than in the absence of the project.
- Market effects, e.g., a project activity of limiting grazing could cause a decrease in cattle supply prompting the market to respond by increasing the price of beef which may then inspire others to increase their cattle cultivation. In this example the project activity would have led to an increase in emissions overall through market effect leakage.

ANNEX BOX 4 ASSESSING RISKS OF NON-PERMANENCE

Carbon assessments seeking carbon finance at the project level must assess permanence of carbon benefits generated by the project, and assess the risk of non-permanence (also known as reversals). Under several standards an insurance "buffer" exists that projects contribute a proportion of emission reductions to that ultimately can compensate for future losses if they occur. A buffer therefore represents carbon gains that will not be able to be sold. The VCS, for example, has a set of tools available to project proponents to estimate risk.41 Alternatively, non-voluntary market payment models for agricultural soil carbon sequestration can design their own mechanism to assess non-permanence risk and develop a corresponding buffer.134

Projects must include in the PDD an assessment of how to mitigate the risk of non-permeance. For example, if a project activity is to transition from tillage to no till, then the project needs to address how long the change of activity will be implemented; are there socio-economic pressures that could force farmers to switch to more profitable (and likely lower soil carbon) land management in the future?

STEP 4

Achieve validation and registration of the project

The project proponent typically selects a validator or verifier from a list of approved expert auditors, which report back to the standard for a final decision on the approval and registration of the project. This process ensures that the methodology has been applied accurately and that the project emissions reductions have been credibly estimated. The verification corroborates the project design, monitoring plan, and evaluation of project impacts and/or safeguards. The validation process involves a desk review, stakeholder interviews and engagement, as well as site visits. These steps inform the final validation report, which sometimes will require the project proponent to undergo a review phase to resolve outstanding issues before validation is final. The final validation report must be submitted for registration of the project. **Emission reductions still have to be verified for the credits to be registered** (see Step 5, *verification and issuance of payment*).

Following successful validation, the project may be registered. Each carbon market standard will have a specific process for registration. Once a project is registered it is formally recognized as eligible to generate credits under the under standard. Standards have registries of verified credits that can be purchased and traded or retired.

STEP 5

Monitoring during the crediting period

The validated monitoring plan included in the PDD must be followed. Project monitoring begins with the start of the project and continues through the life of the project implementation. Monitoring will occur typically either annually or biannually. Carbon benefits or emission reductions generated by the project during implementation are compiled in monitoring reports to be submitted to the standard following standard requirements.

STEP 6 Verification of credits and issuance of payment

Following the submission of each monitoring report, an independent third-party body must verify the emission reductions generated and reported. During verification, an external auditor reviews the monitoring results and certifies the volume of GHG benefits that the project achieved and monitored. After successful verification carbon credits are issued. Some standards (e.g., Gold Standard) might require an additional certification step where the verification report goes through approval of a Technical Advisory Committee before carbon credits can be issued.

Payments for verified offset credits usually occurs only after they have been issued. The exception is when an advance of payment is issued to the project developer to bridge a demonstrated investment gap to carry out project implementation.

Carbon project developers might choose to sell offset credits directly to offset buyers through contracts or agreements not mediated by the carbon standard and its registry. The conditions to do so are agreed between seller and buyer. For this process to be successful and achieve net reductions of greenhouse gas emissions to the atmosphere transparency in offset credits accounting and trading is of paramount importance and the Registry plays a critical role in this transparency.

ANNEX II: CARBON MARKET CONCEPTS

This section introduces core and interlinked concepts that should be addressed and understood in the carbon project development stage to ensure eligibility to deliver credits under existing carbon standards. The definitions provided in this annex is intended to give quick and easy to access definitions; more in-depth guidance about baseline, additionality, leakage, or permanence is available in Annex I.

Carbon ownership

To receive carbon credits a project must demonstrate ownership of the carbon being secured. Where the national/regional laws do not specify the ownership and transfer rights over carbon, there needs to be a careful examination of existing applicable law to determine if the carbon rights can be logically inferred for those holding the rights to that land. Carbon ownership needs to be clearly defined in the Project Design Document (PDD).

Project baseline

The baseline is the carbon emission / sequestration under the business as usual scenario in which no project activities are implemented. The emissions or sequestration are calculated from historical land use and emissions in the project area or representative proxy lands. The elected standard methodology gives requirements for how the baseline must be set.

Additionality

For eligibility, a carbon project needs to demonstrate additionality. This means proving that the emissions reduction would have not occurred in the absence of climate change mitigation funding. Carbon projects need to demonstrate additionality in accordance with the requirements described in the selected accounting methodology of the standard.

Double-counting

A project must also demonstrate that the carbon secured in the project is not already being counted. Double counting can occur through the same emission reduction being issued, used or claimed more than once. Registries have in place careful criteria to assure double-counting cannot occur.

Verified Carbon Credits or Units

Once the carbon credits are issued and registered into a carbon market, they are considered verified carbon credits or units, depending on the carbon market standard. Only verified credits can be traded, to guarantee actual greenhouse gas emissions reductions of those purchasing the carbon credits.

Leakage

Carbon projects must demonstrate that the carbon offset project is not causing leakage of emissions, i.e., an increase of emissions outside of the project boundaries due to activities within the project boundaries. Leakage can be caused by activity shifting (i.e., an activity shifting from within the project boundary to outside of the project boundary) and by market effects (i.e., if the change in project activity changed the supply of a crop which could have the cascading effect of increasing the price and causing a subsequent increase in land dedicated to the product). The leakage of a project is calculated following the methodology laid out for the project in the standard.

Permanence

Permanence refers to the time that the carbon captured by the project stays sequestered (i.e., not emitted to the atmosphere). Sequestered soil carbon can be re-emitted at any point in time practices are reversed or new soil disturbance occurs due to anthropogenic and/or natural causes. The potential impact of these events on project carbon benefits generation is estimated as *non-permanence risks*. A project needs to consider how to mitigate the risk of non-permeance and build that into project design; generally, the project design should consider the driving forces that may lead to non-permeance of the increases in carbon storage into the future and address those factors.

ANNEX III: RESOURCES

This annex provides a reference to resources that could be helpful when implementing a soil carbon project. These include not all-encompassing lists of relevant agencies, projects, methods, and databases available.

AGENCIES & PROJECTS

Carbon Benefits Project (CBP): A project implemented by the UNEP's Division of Global Environment Facility Coordination (DGEF). The project modeling, measuring, and monitoring objective is led by Colorado State University and provides tools for agriculture, forestry and land management projects to estimate the impact of their activities on climate change mitigation. More information available here.

Carbon Monitoring System National Air and Space Administration (NASA): A program designed to make a significant contribution to characterizing, quantifying, and predicting the evolution of local carbon sources and sinks improved monitoring of carbon stocks and fluxes. Its site contains several soil datasets. More information available here.

Carbon sequestration opportunities in soils in Latin America and the Caribbean (LAC): A project funded by FONTAGRO and the Global Research Alliance, aims to contribute to the design of land use and land management with high potential for SOC sequestration in agricultural production systems of LAC. To achieve this goal the project provides LAC countries with tools for reporting their SOC stocks inventories at a Tier 2 and for quantifying project carbon impact. More information available here.

Consultative Group for Agricultural Research (CGIAR): A research consortium made up of 15 independent non-profit research organizations, that works with multiple partners including CIAT to provide resources related to soil health. More information available here.

EU Soil Observatory (EUSO): An online platform that aims to support policymakers by providing resources of soil within Europe. More information available here.

European Soil Data Center (ESDAC): A database portal for soils resources within Europe. More information available here.

Global Soil Partnership (FAO): An intergovernmental technical panel on soils hosted by the FAO. The GSP secretariat uses a bottom up approach to generate collaboration in mapping of global soil organic carbon, Global soil salinity and global soil organic carbon sequestration. More information available here.

ICRAF's Land Degradation Surveillance Framework (LDSF): The project aims to track changes over time and monitor restoration across sub-Saharan Africa. Includes an interactive online spatial database with resources related to soil properties including SOC, total nitrogen, pH, and texture. More information available here.

ISRIC (International Soil Reference and Information Center): Maintain the World Soil Information Service database which aims to safeguard world soil data including legacy data by standardizing multi source data conducting quality control and making it freely available. More information available here.

Inter-American Institute for Cooperation on Agriculture (IICA) Living Soils of America: A specialized agency for agriculture of the Inter-American System that supports member states. The aim of the consortium is to improve rural wellbeing and agricultural development. Check to see if your country is a contributing member of the IICA and relevant resources here.

International Center for Tropical Agriculture (CIAT): A non-profit research and development organization provides resources to assess soil health and monitoring, including a SOC app. More information is available here.

International Soil Modelling Consortium (ISMC): A database of soil models, including descriptions and ways to access models.

Livestock Environmental Assessment and Performance Partnership (FAO-LEAP): A multi-stakeholder initiative that develops comprehensive guidance and methodology to understand and manage the environmental impact of livestock supply chains, including measuring and modelling soil carbon stocks and stock changes in livestock production systems (e.g. grazing lands). The guidance materials are available here.

Society of Ecological Restoration (SER): A professional society which provides a database of restoration projects from around the world including soil restoration. SER does not provide a guarantee of quality of the documentation. More information here.

Soil Information System for Africa- Soils4Africa: A Project launched 2020 to provide open access soil information system (SIS). More information here.

WORLDSOILS: A project developing a SOC map bon with a global spatial resolution of 100m x 100m and a 50m x 50m resolution over Europe. This project is using freely available European Space Agency data and aims to improve modeling of soil organic carbon. More information here.

World Overview of Conservation Approaches and Technologies (WOCAT): A network of Sustainable Land Management (SLM) specialists which hosts a database of different SLM projects and decision support tools. SLM includes but is not limited to soil management. Recommended database by the UN Conservation to Combat Desertification (UNCCD). More information here.

METHODS

Several method standards include webinars and tutorials for practitioners which are highly recommended to complete. See Annex I for details of each standard. Methods approved by voluntary carbon market standards that are applicable to carbon projects internationally in agricultural settings are detailed in Annex Table 13. Additional carbon market methods applicable only to the United States of American are provided by the American Carbon Registry (ACR).

Annex Table 13. Methods relevant to soil carbon in agricultural settings that have been approved by voluntary market carbon standards.

Standard	SOC accounting method	Source
Verra. Adoption of Sustainable Agricultural Land Management	Measured or modeled	(VM0017)
Verra. Soil carbon quantification methodology	Measured or modeled	(VM0021)
Verra. Sustainable Grasslands Management	Measured or modeled	(VM0026)
Verra. Adoption of Sustainable Grasslands through Adjustment of Fire and Grazing	Measured or modeled	(VM0032)
Verra. Improved agriculture management	Measured or Modeled	(VM0042)
Gold Standard. Soil C sequestration in croplands and grasslands	Measured, modeled, peer-reviewed publication or Tier 1/2 IPCC approach	Soil Organic Carbon Framework Methodology V1
Plan Vivo. Ecosystem restoration and rehabilitation, improved land management	Modeled	Climate Benefit Quantification Methodology. See the section about agricultural activity

Other resources that are not necessarily approved by carbon market standards but may provide relevant guidance, resources, and methodologies include:

- **Food and Agriculture Organization GSOC MRV Protocol:** Provides protocol on soil MRV processes and best practices, including field sampling and modeling. Accessible here.
- **C-CAFS SAMPLES:** Provides guidance on measuring emissions from agriculture, including soil sampling and modeling, and identifying appropriate mitigation options. Accessible here.
- **IPCC Guidelines:** Provide guidance on accounting for all AFOLU GHG emissions sources, including SOC, and provides default factors for Tier 1 estimates and basic guidance for Tier 2 and 3 approaches. Accessible here.

DATABASES

Relevant global databases can be found in Annex Table 14. Additional high quality regional specific databases may be found from National Agriculture or Soil Departments

Annex Table 14. Global and regional databases relevant to carbon assessments in agricultural settings.

Resource	Description	Reference
Agro-ecological zones	IIASA's and FAO's crop-specific grid-cell databases integrated with: • climate data analysis, • agro-climatic indicators, • biomass/yield reduction assessments under water-limited conditions, agro-climatic constraints, and edaphic and terrain limitations.	IIASA/FAO, 2012. Global Agro-ecological Zones (GAEZ v3.0). IIASA, Laxenburg, Austria and FAO, Rome, Italy. Database and Guidelines are accessible after registration here.
	Global map of Agricultural land in 2000, showing the extent and the intensity of agricultural cultivation (cropland defined as land used for food cultivation), and pasture lands (land used for grazing). Data was derived from remote sensing and inventory data. Available at a 10km resolution.	Ramankutty et al. (2008). Global Biogeochemical Cycles 22: GB1003. Database is accessible for download here.
Soil parameters data	Location-specific top- and sub-soil information on selected soil parameters SOC, pH, water storage capacity, soil depth, cation exchange capacity of the soil, lime and gypsum contents, sodium exchange percentage, salinity, and textural class and granulometry. Project shapefiles can be uploaded for site-specific assessments.	FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO (Rome, Italy) and IIASA (Laxenburg, Austria). Accessible here.
	Global soil standardized datasets including a wide range of physical, chemical, and pedological data, including an uncertainty layer. Available at a 250m resolution.	Soil Grids 2020. ISRIC – Global Soil Data Facility. Accessible here. World Soil Information Service (WoSIS)-derived datasets and products. ISRIC – Global Soil Data Facility. Accessible here.
	Global soil moisture from 1978 to 2019 (ongoing collection), expressed in % saturation. 0.25-degree spatial resolution. Data is presented in daily files, which require robust data processing.	European Space Agency.2020. Soil Moisture Climate Change Initiative (2020 version 5.2). Accessible here.
	Maps of soil chemical properties and nutrients over the continent of Africa includes a layer of organic carbon.	iSDAsoil, Accessible here.
	A database containing soil maps of SOC at a national and regional level. Including but not limited to North and South America as well as Africa.	Carbon Monitoring Systems, Accessible here.
Soil carbon stock	SOC stock map developed with member countries contribution of national soil data generated using standardized methodologies. Data for user-defined areas are provided as average with range and standard deviation.	FAO Global Soil Partnership. 2019. Global Soil Carbon (GSOC) Map. Accessible here.
	Global SOC stock of cropland map developed from Soil Grids. Low spatial resolution (250 m); accessible to general users. Includes a present quantification of SOC on cropland and a modeled future projection.	International Center for Tropical Agriculture (CIAT) and the CGIAR Research Program on Water, Land and Ecosystems (WLE). Global Soil Carbon in Cropland.2017 Accessible here.
	Map of historic, recent and future SOC stock globally at a low spatial resolution (250m). The modeling was done based on the soil grids map for the recent years. The future mapping utilizes an IPCC Tier 1 accounting approach to develop scenarios over the next 20 years.	Sanderman et al. 2020, "Soils Revealed soil carbon futures", Harvard Dataverse, V1 Available on the Soils Revealed platform here.

Climate data	NDC's Climate Data Online has temperate and precipitation data from points around the world since the 1940s, although points in developing countries are scarce.	NOAA's National Climatic Data Center (NCDC). Accessible here.
	Global climate (temperature, precipitation, and other water balance variables) datasets from the early 1900s to the present.	US National Center for Atmospheric Research (NCAR) Climate Data Guide. 2020. Accessible here.
	The FAO Climate information tool hosts a number of climate datasets that can be queried using their user-friendly interface. Data includes temperature and precipitation from 1961-1990.	FAO. AQUASTAT Climate Information Tool. 2020. Accessible here.
Crop calendar	Information on planting, sowing, sowing rates, and harvesting periods of locally adapted crops in country-specific agro-ecological zones. It also provides information on planting material of main agricultural practices.	FAO Crop Calendar. 2010. Accessible here.
IPCC Stratification	Tier 1 parameters and categorization could be used, but because of their regional character, it is not recommended as good practice for site-specific stratification unless no regional or national information is available. Uncertainty would need to be considered and included.	2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 4. Accessible here. • Climate: Annex 3A.5 • Soil: Annex 3A.5 • Biomass: Figure 4.1

LABORATORIES

Reputable laboratories in your area can be identified from local university directories or by contacting national soil science departments. Many regions may also have local agricultural extensions which could also provide resources for soil testing and guidance on well-reputed laboratories. The laboratory will be able to provide guidance on processing the sample, but it is best practice to be familiar with the general laboratory methodologies to be able to vet potential laboratories. **Details on laboratory analyses for soil carbon assessments can be found in Module A**.

ANNEX IV: CASE STUDIES

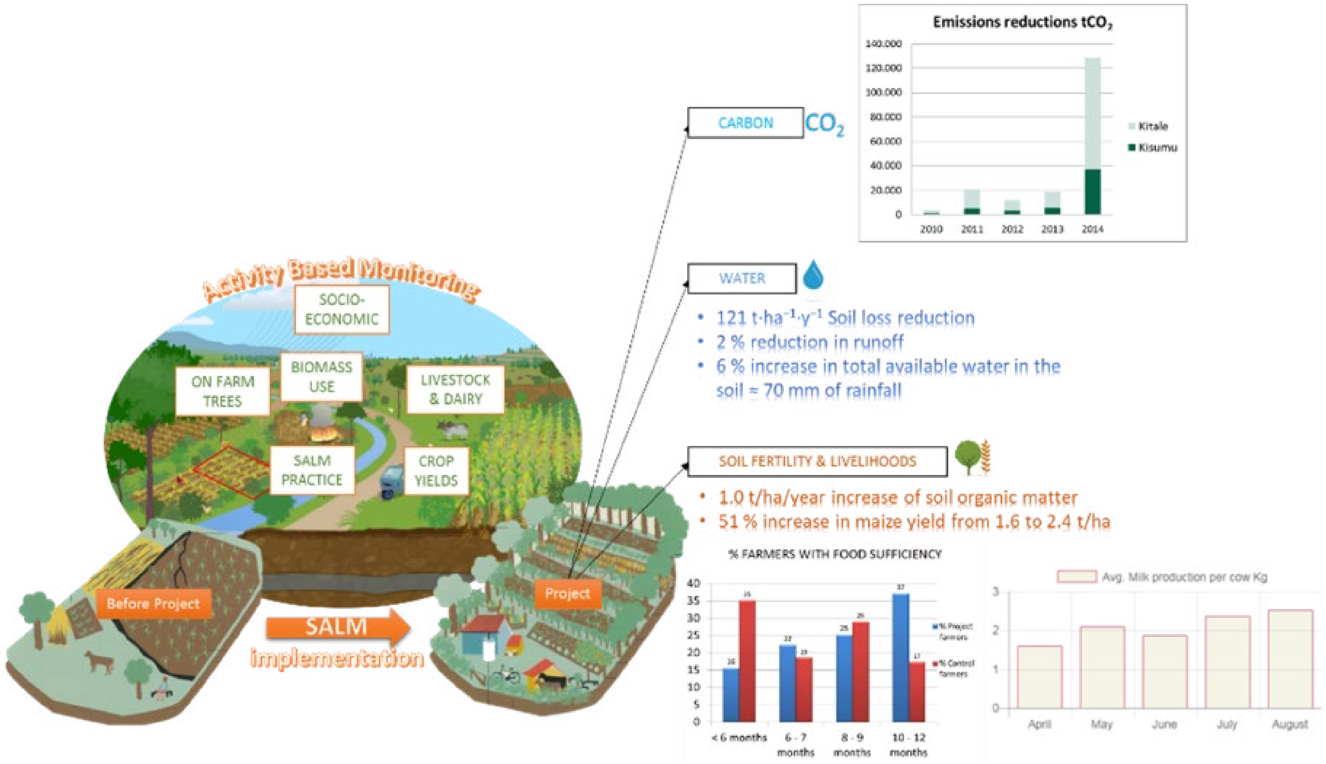
This section provides an overview of a few relevant World Bank-funded projects that implement agricultural practices with an impact on SOC.

SMALLHOLDER ACTIVITY-BASED PROJECT MONITORING AND INFORMATION SYSTEM IN KENYA

A web-based data entry system (the Project MIS system) was adopted to accelerate data entry on a more standardized basis. The web-based system includes a data entry module, which can work offline, and data can be synced to the project server whenever internet is available. The module has several mathematical and logical validations to avoid data entry mistakes, as well as control mechanisms to ensure the quality of data. The data sent to the server is immediately available for further processing using different web-based interfaces. All the calculations to monitor project performance as a whole and to provide the parameters needed for the RothC soil modelling and other calculations related to the SALM methodology, previously done in Excel, are now integrated into the MIS system.

Since 2014, all farm-based data are collected by an SMS phone-based system at farmer group level. Kenya with its M-PESA system of money transfer can be considered the world's leading country in terms of mobile money transfer. Over 17 million Kenyans, equivalent to more than two-thirds of the adult population, use this system on a regular basis. This means that most farmers in the project region are equipped with a simple mobile phone and are well acquainted with its use and handling of SMS messages. Against this backdrop, the annual farm group summary record sheet containing all relevant summary data of a particular farmer group is sent by SMS using a standard protocol.

With this system, the project has flexible options for collecting and entering data into the web-based MIS, either through the data entry interface or directly through the SMS-based system. The proxy indicators collected and self-monitored by the farmers are then used to monitor measurable impacts of multiple project benefits, as illustrated in the chart below (Annex Figure 36).



Annex Figure 36. Multiple impact monitoring from the MIS system. Source: UNIQUE, farm sketches adapted from Vi Agroforestry.

KENYA AGRICULTURAL CARBON PROJECT (KACP) AND THE VERRA VCS SALM METHODOLOGY

The World Bank developed the SALM methodology within the framework of the Kenya Agricultural Carbon Project (KACP). This methodology offers the means to estimate and monitor GHG emissions from project activities that reduce emissions from agriculture through adoption of SALM practices in the agricultural landscape, by applying the activity-based modeling approach. Coupled with published research on management impacts of SOC (to verify model results) this approach is capable to estimate the uncertainty associated with SOC sequestration rates. The methodology offers an ABMS approach to estimate soil carbon stock changes combined with CDM-approved methodological tools to monitor tree carbon sequestration.

The basic idea is that agricultural activities in the baseline will be assessed and adoption of SALM practices will be monitored, as a proxy for the carbon stock changes, using activity-based model estimates. The recommended model to use with SALM is RothC because it calculates the SOC changes due to changes in soil inputs, such as crop residues and manure. The increase or decrease of soil organic matter in the soil is therefore the result of the decomposition of the added organic materials.

SOC MRV DESIGN IN BURKINA FASO AGRICULTURAL CARBON PROJECT (BUFACAP)

The project uses a participatory group approach to register participating community members, provide training and other support, and undertake monitoring. Participating farmers are organized into groups (or are members of already established groups), and the members receive training and capacity-building regarding the implementation of project activities on their lands. The registration of participants, training and capacity-building are undertaken by the extension structure set up by the project, which includes the staff of respective implementing partners, as well as lead (exemplary) farmers from within the farmer groups. Additional training is provided by government extension staff and Non-Governmental Organization (NGO) development projects.

The monitoring system includes two types of monitoring: permanent farm monitoring (PFM) and Farmer Group Monitoring (FGM). The main distinction between the two is that PFM is implemented entirely by the project staff (field extension and M&E unit) on a selected representative sample of farms being, hence, representative of the entire project area. Meanwhile, the FGM is a farmer-self assessment, whereby each of the contracted farmer groups self-collect annual records of all data, which are needed to monitor the project and report the data to the field extension staff. The PFM is used to establish the project baseline and compare with the FGM data as a quality control measure. The

FGM provides the data used to quantify the project's climate mitigation outcomes (t CO_2e).

In this project, the roles and responsibilities of different institutions for SALM monitoring have been elaborated separately according to the type of monitoring – permanent farm monitoring or farmer group monitoring (Annex Table 15).

Annex Table 15. Roles and responsibilities in permanent farm monitoring and farmer group monitoring. Source: UNIQUE.

Institution	Roles and responsibilities
Roles in permanent farm monitoring	
Monitoring and Evaluation Unit	• Overall coordination of monitoring system • Training technicians in data collection techniques and use of data collection forms • Supporting technician training (training of trainers' approach) on SALM practices to be introduced by the project (e.g. in cooperation with Vi Agroforestry) • Verify data quality at the producer level (sample of producers) • Transmit the refined information to the database
Advisory Unit	• Provide lessons learnt from Kenya field visit on a demand driven basis
Field extension staff	• Train producers in techniques and practices related to agricultural resources • Technically assist the implementation of best practices • Check the quality of the data collected • Ensure the application of the best practices adopted
Roles in farmer group monitoring	
Local Facilitator	• Assist the producers in filling out data collection forms • Collect information from farmer groups • Verify and collect the data • Pass on collected information to project field extension staff • Ensure the practical implementation of the SALM practices adopted
Farmer group	• Collect farm-based activity data on the following, via data collection forms • Pass on information on agricultural yields, livestock, trees etc. to the Local Facilitator

NIGER COMMUNITY ACTION PROJECT FOR CLIMATE RESILIENCE (NIGER CAPCR)

These Sustainable Land and Water Management (SLWM) practices implemented by the project cover a wide spectrum of field practices of which many are relevant to soil carbon sequestration, in particular: cropland management (mulching, reduced tillage, crop rotation, agroforestry), soil and water conservation measures (small water retention/water run-off infrastructure), vegetative measures (vegetated strips, windbreaks, assisted natural regeneration, dune fixation, bushfire management), and development of grazing areas (fodder). To date, the project has implemented SLWM on around 4,800 ha of cropland and 38,900 ha of silvopastoral areas. The project monitoring further reports an average crop yield increase of about 50% while forage yield increased by 15%.

This national program has established a basic MRV system to report on the main indicators on a national scale. As an overview the following indicators are collected and reported:

- Information on financing provided for different SLWM practices is annually collected at the commune level;
- There is no monitoring of practices and practice changes at farmer field level;
- The agricultural productivity of the main crops is evaluated annually, relative to control sites, including the evaluation of biomass in general (herbaceous, wet/dry biomass); and
- Geo-referencing information on all implementation sites.

Overall, this current MRV design does not represent a project or activity-based approach rather than a wholesale approach for reporting of SLWM financing on a national scale. Since also other SLWM projects are being implemented in Niger, the question arises how an adequate MRV system should look like where SOC is used as an indicator (among others) for SLWM performance in order to reward the national efforts, for which minimum information is available.

ANNEX V: GLOSSARY OF TERMS

Activity data: Data on the magnitude of human activity resulting in emissions or removals taking place during a given period.

Additionality: Demonstration that the carbon offsets area direct consequence of the project activity and would have taken place without intervention.

Baseline emissions: Measurement, calculation, or time used as a basis of comparison from which the offset can be calculated.

Bulk density: A common measure of soil which reflects the structural integrity. Dry weight of the soil divided by its volume.

Carbon flux: Carbon exchanged between carbon pools over a certain time

Carbon intensity: The amount of carbon by weight emitted per unit of activity data.

Carbon Sequestration: The removal of carbon dioxide from the atmosphere, in the land use sector removals captured in biomass or the soil.

Climate Smart Agriculture (CSA): Agriculture that sustainably increases productivity, enhances adaptive capacity and reduces or removes GHG where possible. Alternative agricultural schemes include conservation agriculture or regenerative agriculture.

Conservation agriculture: Defined by the Food and Agriculture Organization (FAO) of the UN as agriculture practices that promote minimal soil disturbance, maintenance of permeant soil cover and diversification of plant species. Alternatives include Climate Smart Agriculture or Regenerative Agriculture.

Crop residues: A major contributor to SOC, plant (root, stalk, leaf) residues that are less than 2 mm in size found throughout the soil column, primarily in topsoil.

Emissions: The release of a substance into the atmosphere, within the context of climate change refers to the release of a greenhouse gas into the atmosphere.

Greenhouse gas (GHG): Any gas that absorbs infrared radiation in the atmosphere causing a greenhouse effects. GHG include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrochlorofluorocarbons (HCFCs), ozone (O_3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

Hectare (ha): A metric unit of a square measure equal to 10,000 square meters.

Horizon (Soil): A layer in the soil profile that has a psychical, chemical, and biological characters that differ from the layers above and below.

Humus: Decomposed organic materials found at the near surface horizons. Represents one of the most stable forms of SOC.

Intergovernmental Panel on Climate Change (IPCC): Established jointly by the United Nations Environment Program and the World Meteorological Organization in 1988, the purpose of the IPCC is to assess information in the scientific and technical literature related to the issue of climate change. With its capacity for reporting on climate change, its consequences, and the viability of adaptation and mitigation measures, the IPCC is also looked to as the official advisory body to the world's governments on the state of the science of the climate change issue.

Leakage: An increase of emissions outside of the project boundaries due to shifting activities within project boundaries.

MRV: Monitoring, Reporting, and Verification of the carbon benefits or GHG emissions of the project.

Net ecosystem exchange: The total net flux in carbon between atmosphere, plants, and soils, representing the change in carbon storage in an ecosystem.

Permanence: In carbon accounting, time that the carbon captured by the project stays sequestered.

pH: A measure of acidity or alkalinity of a substance.

QA/QC: Quality Assurance/Quality Checks.

Sequestration: When referring to carbon, it is the process by which CO_2 is removed from the atmosphere and held in solid form.

Soil core: A cylindrical sample of soil taken in the field.

Soil carbon stock: The amount of organic carbon found in the soil per unit of area.

Soil organic carbon (SOC): Carbon found in the form of soil organic compounds in living or decaying biological matter.

Soil inorganic carbon: Carbon found in soil mineral forms either formed through weathering of parent materials or from a chemical reaction (e.g., calcification).

Regenerative agriculture: A system of farming principles that increase biodiversity, enriches soils, improves watersheds, and enhances ecosystem services, with an aim to capture carbon in soil and above ground biomass, reversing current global trends of atmospheric accumulation.

Residence time: The amount of time that carbon is held in each portion of the carbon cycle.

Remote sensing: The process of detecting a monitoring the physical characteristics of an area on land by measuring its reflected and emitted radiation at a distance. Can refer to images from low flying drones or longer distance satellites.

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