CHAPTER 9.

Land management net biogenic CO_2 emissions

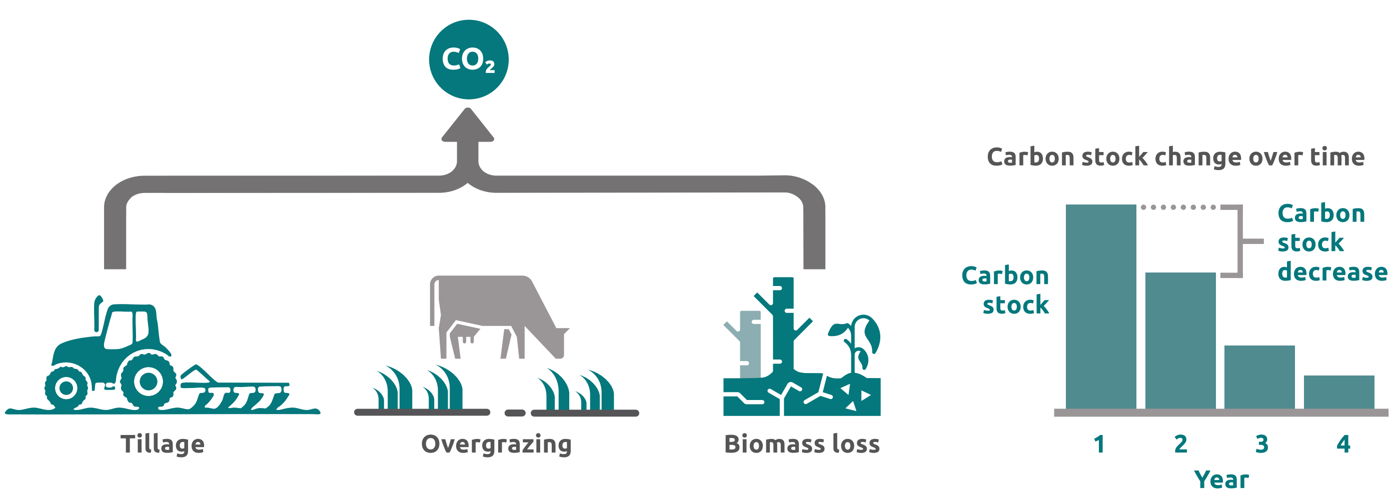
This chapter provides requirements and guidance on accounting for net biogenic CO_2 emissions from land management activities on lands remaining in the same land use (e.g., agricultural management activities on existing agricultural land), from both a scope 1 and scope 3 perspective.

9.1 Overview

Land management net biogenic CO_2 emissions are net biogenic CO_2 emissions that occur due to management actions on land that remains in the same land use category or subcategory in the reporting year. Land management activities on existing agricultural land (e.g., field preparations or harvests) can impact land-based carbon pools, including above- and below-ground biomass, dead organic matter, and soil carbon pools (Figure 9.1).

- Land management net biogenic CO_2 emissions are calculated using a stock change accounting approach. Companies are required to estimate the net land carbon stock change for all required carbon pools (Requirement 14). If the net land carbon stock change decreases, the difference is accounted for as land management net CO_2 emissions. If the net land carbon stock change increases, the difference may be accounted for as land management CO_2 removals. Land management CO_2 removals, if reported, are accounted for separately from emissions and are subject to additional accounting and reporting requirements (see Chapter 13).
- GHG inventories are designed to account only for direct anthropogenic impacts on land carbon stocks. All changes in land carbon stocks on existing productive agricultural land are considered anthropogenic (Requirement 15).

Figure 9.1 Examples of net land carbon stock changes



9.2 Requirements

9.2.1 Accounting requirements

REQUIREMENT 14:

***Land management net biogenic CO_2 emissions accounting*[1]**

Companies **shall** account for land management net biogenic CO_2 emissions on productive agricultural lands according to the following requirements:

- **Accounting approach**: Companies **shall** account for land management net biogenic CO_2 emissions based on annual or annualized net land carbon stock losses occurring in the reporting year using stock-change accounting methods.
  - Companies **may** account for cropland carbon stock changes using monitoring frequencies at timescales that reflect the relevant crop rotation or crop cultivation cycle. See Section 9.4.3 in the *Guidance* for additional details.
- **Spatial boundaries**: See Requirement 5 to define the scope 1 and scope 3 spatial boundaries.
  - **Scope 1**: Companies **shall** account for net land carbon stock changes from land management activities on all agricultural land in their scope 1 spatial boundary.
  - **Scope 3**: Companies **shall** account for net land carbon stock changes on all:
    - attributable productive lands in relevant jurisdictions or sourcing regions (see Requirement 6)
    - productive lands and, if applicable, proximate and adjacent non-productive lands (see Requirement 7) within relevant LMUs
    - productive lands within relevant harvested areas
    - lands related to leased assets, franchises, and investments in their scope 3 spatial boundary
- **Carbon pools and land uses**: Companies **shall** account for the net land carbon stock change (rather than assuming no carbon stock change) for the following carbon pools:
  - **Biomass carbon stock changes**, including above-ground and below-ground biomass on:
    - all forest lands
    - grasslands, croplands, wetlands, and/or settlements with woody or permanent cover
  - **Dead organic matter carbon stock changes**, including dead wood and litter on:
    - forest lands, grasslands, and croplands where management practices significantly impact woody residues
  - **Soil carbon stock changes**, including soil organic carbon in mineral and organic soils on:
    - all grasslands and croplands
    - forest lands, wetlands, and settlements where management practices significantly disturb soils

  Companies **may** account for net land carbon stock changes for all carbon pools in all land uses (e.g., account for biomass carbon stock changes in grassland with no woody or permanent vegetation).
- **No emissions**: If carbon stocks increase, companies can choose to report zero emissions and are not subject to comply with removals requirements (as long as they report zero removals as well).

REQUIREMENT 15:

Anthropogenic impacts on agricultural land[1]

All changes in land carbon stocks on productive agricultural land in the reporting year are considered anthropogenic. Companies **shall** fully account for all net land carbon stock losses on all agricultural lands in the reporting year, including changes due to degradation and carbon stock losses from fires, storms, and other natural disturbances.

Box 9.1 Accounting for land management net biogenic CO_2 emissions and land management CO_2 removals on forest lands and non-productive, non-forest lands

To compile a complete and accurate GHG inventory, companies that own or control forest lands, companies that own or control other non-forest lands outside of agricultural production, companies that source forestry products (e.g., timber, paper, pulp, wood pellets, resins, etc.), and/or companies that include proximate and adjacent non-productive lands in their scope 3 spatial boundary for agricultural products they source, need to account for how their harvesting, management, and/or purchasing activities result in land management net biogenic CO_2 emissions and land management CO_2 removals. The IPCC states that "anthropogenic emissions and removals means that greenhouse gas emissions and removals included in national inventories are a result of human activities" (IPCC 2006, 1.4; 2019a). However, distinguishing anthropogenic from non-anthropogenic emissions or removals due to forest management activities or land management on non-forest lands outside of agricultural production is complex. This is because forest lands and non-productive, non-forest lands emit and remove CO_2, and do so both because of and despite human activities.

Rules for accounting for emissions and removals on forest lands and non-productive, non-forest lands in corporate GHG inventories have not been decided on by the Independent Standards Board of the GHG Protocol. Final accounting requirements and guidance for land management net biogenic CO_2 emissions and land management CO_2 removals on forest lands and other non-forest lands outside of agricultural production may be published in future versions of this *Standard* (see Box 1.1).

9.2.2 Reporting requirements

Reporting requirements for land management net biogenic CO_2 emissions

Companies **shall** report:

- Net land carbon stock losses in the "land management net biogenic CO_2 emissions" accounting subcategory under "land emissions" in the physical GHG inventory.

Companies **shall** disclose the following information in their GHG report:

- **Accounting approach**: Whether one year or a longer period was used to calculate the annual or annualized carbon stock loss.
- **Carbon pools and land uses**: The specific land carbon pools included in their analysis of net carbon stock changes, including when "no carbon stock change" is assumed for a particular carbon pool and land use.

9.3 Recommendations

Gross biogenic land CO_2 emissions reporting

Companies **should** also account for and separately report "gross biogenic land CO_2 emissions" as a disaggregated accounting subcategory of "gross CO_2 fluxes." Disclosing "gross biogenic land CO_2 emissions" provides additional transparency to the gross land carbon stock losses contributing to estimates of the net land carbon stock change (e.g., the gross land carbon stock losses associated with fire or other natural disturbances included when estimating the net land carbon stock change).

9.4 Guidance on the requirements and recommendations

9.4.1 Relationship between land management biogenic CO_2 emissions and other accounting subcategories

Land management net biogenic CO_2 emissions are net biogenic CO_2 emissions that occur due to management practices on land that remains in the same land use category or subcategory in the reporting year. In contrast, land use change emissions (see Chapter 7) include any release of GHG emissions due to a *change* in land use from one land use category or subcategory to another.

Land management net biogenic CO_2 emissions (and land management CO_2 removals; see Chapter 13) on productive agricultural lands are accounted for based on the annual (or annualized) net carbon stock change in all land-based carbon pools, within the relevant scope 1 or scope 3 spatial boundary (see Sections 9.4.3 and 9.4.4 for further guidance on temporal and spatial considerations, respectively). Note that land management net biogenic CO_2 emissions and land management CO_2 removals due to land management activities on forest lands and non-productive lands are not covered under this version of the *Standard* (see Box 9.1 for details).

Land management net biogenic CO_2 emissions represent annual net losses in land-based carbon pools, while land management CO_2 removals represent annual net gains in land-based carbon pools. Accounting for removals, including land management CO_2 removals, is subject to additional accounting requirements (see Chapters 12 and 13).

For transparency, this *Standard* also recommends that companies account for and report *gross* biogenic land CO_2 emissions and *gross* removals, using a flow accounting approach (see Sections 9.4.2 and 3.4.4 for additional guidance).

Land management activities also produce other GHGs besides biogenic CO_2, including methane (CH_4), nitrous oxide (N_2O), and non-biogenic (i.e., fossil) CO_2 emissions. These emissions are accounted for as land management production emissions (see Chapter 10).

9.4.2 Overview of accounting approaches for land management biogenic CO_2 emissions

Stock change (net) versus flow (gross) accounting

This *Standard* requires that companies account for and report land management net biogenic CO_2 emissions (and land management CO_2 removals, if companies optionally report removals) using the stock change accounting approach (Table 9.1; see Section 3.4.4 for additional guidance). Net land carbon stock decreases are accounted for as land management net CO_2 emissions. Net land carbon stock change increases may be accounted for as land management CO_2 removals, subject to additional removals accounting requirements (see Chapters 12 and 13). The stock-change accounting approach can be operationalized using either the Stock-Difference accounting method (Equation 9.1) or Gain-Loss accounting method (Equation 9.2).

Table 9.1 Accounting approaches for land management net biogenic CO_2 emissions and removals

Accounting approach	Is this approach required?	Description
Stock change accounting approach	**Required**	An accounting approach that estimates the net flux of carbon to or from the atmosphere during a time period, based on the net change in carbon stocks in the system at the beginning and end of that period. This approach can be operationalized using the Stock-Difference accounting method (Equation 9.1 in Section 9.5.3.1) or the Gain-Loss accounting method (Equation 9.2 in Section 9.5.3.1).
Flow accounting approach	Optional	An accounting approach that estimates emissions and removal flows by estimating the gross fluxes of carbon to and from the atmosphere based on the flows of carbon from the atmosphere to the system (i.e., gross removals) and flows of carbon from the system to the atmosphere (i.e., gross emissions).

The flow accounting approach accounts for emissions and removal flows separately by estimating the *gross* fluxes of carbon to and from the atmosphere (Table 9.1; see Section 3.4.4 for additional guidance). Flows of carbon from the atmosphere to the system are accounted for as gross removals, and flows of carbon from the system to the atmosphere are accounted for as gross emissions. Flow accounting-based information also serves as the parameters for estimating the net land carbon stock change using the Gain-Loss Method (Equation 9.2). Therefore, the data used for the flow accounting approach can optionally be used to estimate both *gross* biogenic land CO_2 emissions (and *gross* removals) and the *net* biogenic CO_2 flux.

As set forth in Section 9.3, companies are recommended to account for and separately report land management gross biogenic CO_2 emissions. Companies may also account for and report gross biogenic land CO_2 removals, as set forth in Section 12.3. Accounting and reporting information based on both stock change and flow accounting approaches is recommended to ensure transparency of individual gross biogenic carbon fluxes, identify drivers of net carbon stock changes (e.g., types of disturbances leading to gross biogenic land CO_2 emissions or growth rates driving gross biogenic land CO_2 removals), and to supplement reporting of net carbon stock changes. For further discussion on the stock change accounting framework set forth in this *Standard*, see Section 3.4.4.

Carbon pools and land uses

The information in Table 9.2 provides an overview of what carbon pools, at a minimum, must be included when estimating anthropogenic carbon stock changes across different land use types, as set forth in Requirement 14. Table 9.2 also provides an overview of whether accounting requirements and guidance for land management net biogenic CO_2 emissions by land use type are covered in version 1 of this *Standard* (see Box 9.1 and Box 1.1 for details).

Table 9.2 Carbon pools to include when accounting for land management net biogenic CO_2 emissions

Land use		Relevant products	Are carbon stock changes anthropogenic?	Carbon pools included, at a minimum, when estimating carbon stock changes (see Requirement 14)
Cropland	All cropland is productive by definition	Crops (e.g., food, feed, and fibre), bioenergy feedstocks	All changes in land carbon stocks are considered anthropogenic (**see Requirement 15**)	• Biomass (above- and below-ground) on croplands with woody or permanent cover • Dead organic matter, including dead wood and litter, when management practices significantly impact woody residues • Soil carbon, including soil organic carbon in mineral and organic soils
Grasslands	Productive grassland	Animal products		• Biomass (above- and below-ground) on grasslands with woody or permanent cover • Dead organic matter, including dead wood and litter, when management practices significantly impact woody residues • Soil carbon, including soil organic carbon in mineral and organic soils
	Natural grassland	NA	Accounting for land management net biogenic CO_2 emissions on non-productive grasslands is not covered in v1 of this *Standard* and *Guidance*	
Wetlands	Productive wetland	Aquaculture products	All changes in land carbon stocks are considered anthropogenic (**see Requirement 15**)	• Biomass (above- and below-ground) on wetlands with woody or permanent cover • Soil carbon, including soil organic carbon in mineral and organic soils, where management practices significantly disturb soils
	Natural wetland	NA	Accounting for land management net biogenic CO_2 emissions on non-productive wetlands is not covered in v1 of this *Standard* and *Guidance*	
Forest lands		Forest products	Accounting for land management net biogenic CO_2 emissions on forest lands is not covered in v1 of this *Standard* and *Guidance*	
Settlements		NA	All changes in land carbon stocks are considered anthropogenic	• Biomass (above- and below-ground) on settlements with woody or permanent cover • Soil carbon, including soil organic carbon in mineral and organic soils, where management practices significantly disturb soils

9.4.3 Time considerations for land management net biogenic CO_2 accounting

Land management net biogenic CO_2 emissions are accounted for based on the annual net land carbon stock change or the net land carbon stock change annualized over a longer monitoring frequency. The annual or annualized net land carbon stock change can be calculated based on two methods:

- **Stock-Difference method**: This estimates the difference between land-based carbon stocks annually or annualized between two points in time (see Equation 9.1 in Section 9.5.3); or
- **Gain-Loss method**: This estimates the difference between annual gross carbon gains and annual gross carbon losses to land-based carbon pools within the reporting year (see Equation 9.2 in Section 9.5.3).

Carbon stocks should be monitored annually to quantify annual stock changes, using either the Gain-Loss or Stock-Difference method. If annual monitoring is not possible, net carbon stock change estimates may be annualized based on longer monitoring frequencies that reflect the frequency of the relevant land management activity (e.g., the crop production cycle or rotation period), using the Stock-Difference method.

When determining the appropriate monitoring frequency for estimating land carbon stock changes, companies should consider the following:

- The land management practices and frequency of those practices, and how both are expected to impact carbon stocks across all land-based carbon pools
- The expected magnitude of carbon stock changes on lands within the relevant spatial boundary, especially relative to the uncertainty associated with estimations of carbon stock changes in that area
- The cultivation cycle of the product purchased by the reporting company and/or any crop rotations associated with that product
- Recommended monitoring techniques and protocols for the given land use, sector, and carbon pool
- Cost effectiveness of the monitoring process
- Impact and frequency of unexpected events, such as natural disturbances

As set forth in Section 9.2.2, companies are required to report the monitoring approach and frequency used to estimate land management net biogenic CO_2 emissions for each relevant land use and/or activity in their scope 1 or scope 3 inventory. For general guidance on setting the time boundary when accounting for different accounting categories, see Section 4.4.4.

If land carbon stock changes are estimated based on direct measurements of carbon stocks over time within a given scope 1 or scope 3 spatial boundary (e.g., an LMU or set of LMUs), companies should strive to implement an inventory or sampling protocol with annual sampling of a subset of plots or strata (for a general discussion of strata and stratification, see Section 6.4.2.1). Where annual data collection is not possible, the resampling of plots should occur at least every five years to estimate the annualized land carbon stock change. The exact sampling interval (i.e., between one and five years) should follow best practices and evidence from peer-reviewed literature that establishes the sampling frequency needed to detect changes in carbon stocks in the relevant carbon pool(s), land use, and so on, on lands within the given spatial boundary.

9.4.4 Spatial boundaries for land management net biogenic CO_2 emissions accounting

Requirements and guidance for setting the scope 1 and scope 3 spatial boundaries are set forth in Chapter 5. The requirements and guidance in Chapter 5 also set forth what lands must be included or excluded when applying certain scope 1 and scope 3 spatial boundaries to complete the accounting. For scope 3 accounting, the net land carbon stock change is calculated across all attributable productive lands within jurisdiction-level and sourcing region-level scope 3 spatial boundaries and across all productive agricultural lands within LMU-level and harvested area-level scope 3 spatial boundaries. This *Standard* does not cover accounting for net land carbon stock changes due to land management activities on forest lands and non-productive, non-forest lands occurring within the scope 1 or scope 3 spatial boundary (see Table 9.2, Section 9.4.6, and Box 9.1 for details).

Note that this *Standard* sets forth greater flexibility for setting the scope 3 spatial boundary when accounting for land management net biogenic CO_2 emissions compared to when optionally accounting for removals, including land management CO_2 removals (see Chapters 12–13). Data specific to sinks and pools (i.e., corresponding to more granular levels of traceability) are required to meet the permanence principle and balance accuracy and conservativeness when accounting for and reporting land management CO_2 removals.

9.4.5 Determining anthropogenic impacts on productive agricultural land

GHG inventories are designed to account only for anthropogenic impacts on land carbon stocks. Land-based carbon pools are also impacted by natural (i.e., non-anthropogenic) factors (e.g., storms, fires, and other natural disturbances) and indirect anthropogenic factors (e.g., CO_2 fertilization effects and longer growing seasons due to climate change).

As set forth in Requirement 15, all changes in land carbon stocks on productive agricultural land in the reporting year are considered anthropogenic. Agricultural land is the total of cropland, permanent meadows, and pastures. All cropland is by definition productive. Grasslands and wetlands can encompass both productive and natural (i.e., non-productive) grasslands and wetlands (see Table 9.2 and Section 3.4.2 for further details on the land use typology used in this *Standard*). Examples of productive agricultural lands include croplands directly producing annual or perennial crops, productive grasslands (e.g., pastures) used for grazing in livestock production systems, and land producing agricultural products within agroforestry production systems that do not meet forest land use thresholds. Companies must fully account for all net land carbon stock losses on all productive agricultural lands in the reporting year, including changes due to degradation and carbon stock losses from natural disturbances. Natural disturbances may include wildfires, pest and disease infestations, extreme weather events, and/or geological disturbances, beyond the control of, and not materially influenced by, the company. See Table 9.2 for an overview of carbon pools that must be included, at a minimum, by land use type when accounting for land management net biogenic CO_2 emissions.

Many companies already have internal strategies to address natural disturbances to help ensure the ongoing supply of products. In the same way, the impact of natural disturbances on carbon stock changes on agricultural lands may also need to be considered, especially when companies seek to meet targets.

Assessing the impact of natural disturbances on carbon stock changes on agricultural lands is typically easier for scope 1 accounting, as the company has control over the land. For scope 3 accounting, companies need to understand how the data and/or methods used to account for net land carbon stock changes on agricultural lands in their relevant scope 3 spatial boundaries treat natural disturbances. For example, when regional or national data are used (i.e., corresponding to regional or national levels of traceability and scope 3 spatial boundaries), these data may have excluded natural disturbance emissions either directly (through the application of accounting rules) or indirectly (using methods that do not assess natural disturbances).

9.4.6 Determining anthropogenic impacts on forest lands and non-productive, non-forest lands

Because forest lands and non-productive, non-forest lands emit and remove CO_2, both due to and despite human activities, separating anthropogenic from non-anthropogenic emissions or removals due to forest management activities or land management activities on non-productive, non-forest lands (e.g., non-productive grasslands and wetlands) outside of agricultural production is complex. Recent peer-reviewed research has highlighted how different definitions of "anthropogenic" CO_2 removals have implications for national GHG accounting and international climate targets (see Box 9.2). Meanwhile, national and corporate-level GHG inventories exhibit some key differences, especially for scope 3 accounting (see Section 3.4.5).

Rules for accounting for emissions and removals on forest lands and non-productive, non-forest lands in corporate GHG inventories have not been decided on by the Independent Standards Board of the GHG Protocol (see Box 9.1). Final accounting requirements and guidance for land management net biogenic CO_2 emissions and land management CO_2 removals on forest lands and other non-productive lands outside of agricultural production may be published in future versions of this *Standard*.

Box 9.2 Defining and separating anthropogenic from non-anthropogenic land emissions and removals on forest lands

THE IMPLICATIONS OF DIFFERENT DEFINITIONS OF "ANTHROPOGENIC" FOR GHG ACCOUNTING

The separation of natural and anthropogenic emissions in national greenhouse gas inventories has been a topic of long-running discussions in international climate policy (UNFCCC 1997; UNFCCC 2001). These discussions typically focus on definitions of natural versus anthropogenic events, and methods for separating their effects. More recently, research has highlighted differences in how anthropogenic CO_2 removals are defined, and the implications of these differences for national GHG accounting and international climate targets.

Recent studies have investigated a gap of 6–7 billion tonnes of CO_2 per year globally between the emissions reported by national GHG inventories (NGHGIs), which inform country commitments under the Paris Agreement, and those estimated by global models used in IPCC assessments, which determine emissions pathways consistent with the Paris Agreement goals (Grassi et al. 2021; Lamb et al. 2026). This gap, equivalent to about 15 percent of global emissions, is largely explained by different definitions of anthropogenic CO_2 emissions and removals in managed forests (Friedlingstein et al. 2025; Gidden et al. 2023; Grassi et al. 2018, 2021, 2023; Lamb et al. 2026; Schwingshackl et al. 2022). In short, NGHGI reporting definitions of the term "anthropogenic" incorporate a significant portion of the removals that are attributed to non-anthropogenic activities in IPCC assessment reports.

Other studies have highlighted the implications of this large discrepancy for net-zero CO_2 emissions targets to stabilize global temperatures (Allen et al. 2025; Grassi et al. 2025). In July 2024, an IPCC Expert Meeting on "Reconciling Anthropogenic Land Use Emissions" was convened in Ispra, Italy, to begin to address this issue and to inform the scoping process of the IPCC's Seventh Assessment Report (AR7).[a] The results of this summit are summarized in the Report of the IPCC Expert Meeting (IPCC 2024).

CHALLENGES IN SEPARATING ANTHROPOGENIC FROM NON-ANTHROPOGENIC LAND EMISSIONS AND REMOVALS

Examples of methodological challenges for distinguishing anthropogenic from natural impacts on land emissions and removals include:

- Using a plot-based, stock-difference method to estimate carbon stock changes using periodic measurements (i.e., multi-year sampling) cannot separate out what factors (i.e., anthropogenic vs. natural) influence land carbon stock changes.
- Legacy effects of carbon stocks based on past management or natural disturbances can influence the potential for emissions or removals (e.g., lands with historically low carbon stocks during a base period have more potential for removals).
- Natural disturbances lead to a relatively rapid loss of carbon stocks, which is then followed by a slower re-accumulation of carbon as the land recovers.

Note: a. For further details, see Joint Research Centre of the European Union 2024.

9.4.7 Evaluating uncertainty in data when accounting for land management net CO_2 emissions

Data used to estimate land management net biogenic CO_2 emissions should fall within uncertainty ranges published in the peer-reviewed literature or other reports for carbon stocks and growth rates associated with lands in the corresponding climate, ecological zone, soil type, and so on. Volume 4 in the *2006 IPCC Guidelines for National GHG Inventories* (IPCC 2006) and the *2019 Refinement* (IPCC 2019a) provide estimates of carbon stocks, growth rates, and carbon stock change factors for biomass, dead organic matter, and soil carbon pools, as well as their uncertainty ranges. Secondary data used to estimate land carbon stock change should fall within the given IPCC uncertainty ranges.[2] If data used to estimate changes in carbon stocks (e.g., carbon stocks, growth rates, or carbon stock change factors) fall outside the uncertainty thresholds published in relevant IPCC publications, primary data should be collected and disclosed to verify estimated carbon stock changes.

General guidance for estimating and reducing uncertainty and improving data quality over time is discussed further in Section 6.4.4.

Box 9.3 General challenges for complete and accurate carbon stock change accounting

Accounting for land carbon stock changes on agricultural land is complicated by several factors, including:

- **High spatial variability**: Carbon stocks within a given landscape can be highly variable based on both natural (e.g., climate, vegetation and soil, geology, topography, etc.) and anthropogenic (e.g., land use, current management practices, historic management, etc.) factors. Accounting for this spatial variability is essential to ensure comprehensive and accurate estimates of land carbon stock changes. An assessment that fails to capture spatial variation in carbon stocks is likely to produce highly uncertain estimates of carbon stock changes. This is especially true when accounting at relatively broader scope 3 spatial boundaries (e.g., sourcing region or jurisdictional boundaries) because high levels of uncertainty at local scales can amplify to larger errors at broader scales if sampling is biased or otherwise not representative of all lands included in the spatial boundary.

  Comprehensive estimates can be achieved through inventory or sampling approaches that estimate land carbon stocks within a given area or stratum (i.e., carbon stocks specific to given strata based on climate, ecological zone, soil type, land use, management practices, etc.), or with models (e.g., forest growth and yield models or soil biogeochemical models) that mechanistically represent the relationship between carbon pools and the factors influencing the rate of carbon stock changes specific to a given location and management activities. In either case, estimates should be calibrated against empirical measurements.

- **Rapidly lost, slow to increase**: Carbon stock losses in biomass and soil carbon pools occur at different rates than carbon stock gains. Carbon stocks can decrease relatively quickly due to a single event, such as a harvest, soil cultivation, or natural disturbance. Meanwhile, gains in carbon stocks increase at more modest rates over time, due to biomass growth or the gradual accumulation of soil carbon. Similarly, the rate of carbon stock change can be small relative to the total, overall carbon stock, the spatial variability in carbon stocks, or the precision of methods used to estimate carbon stocks. Land carbon stock changes can also exhibit high temporal variability due to other factors such as yield variability and the impacts of disturbances (e.g., more frequent extreme weather events) driven by climate change.

  Measurement and monitoring of land carbon stocks should balance the trade-off between detecting short-term annual carbon losses (i.e., that may require higher levels of temporal and spatial resolution) and accurately measuring longer-term carbon gains (i.e., that accumulate gradually) across the entire spatial boundary.

- **Methods are still developing and data gaps remain**: Despite continued research and technological innovation, the remote sensing of above-ground biomass and associated carbon stocks still faces barriers to widespread deployment due to limited data availability (i.e., data needed to calibrate biomass estimates and harmonize datasets to compare maps at multiple points in time) and bias in the data (i.e., underestimating high biomass values and overestimating low values), though these limitations are subject to continual improvements. Other carbon pools, such as soil carbon, cannot be directly estimated through remote sensing alone, thus requiring the use of carbon stock change factors, models, and direct measurement. Soil carbon monitoring is currently concentrated in Annex I countries and less so in non-Annex I countries. Proximal methods for soil carbon sampling, like handheld infrared sensors, have promise but are not sufficiently developed for widespread deployment.

9.5 Calculating land management net biogenic CO_2 emissions

Figure 9.2 provides an overview of the calculation guidance in Section 9.5. Section 9.5.3.1 provides general calculation guidance that applies to calculating land carbon stocks across all land-based carbon pools. Sections 9.5.3.2–9.5.3.4 provide calculation guidance and methods for estimating carbon stock changes across specific land-based carbon pools, including biomass carbon stock changes (Section 9.5.3.2), dead organic matter carbon stock changes (Section 9.5.3.3), and soil carbon stock changes (Section 9.5.3.4).

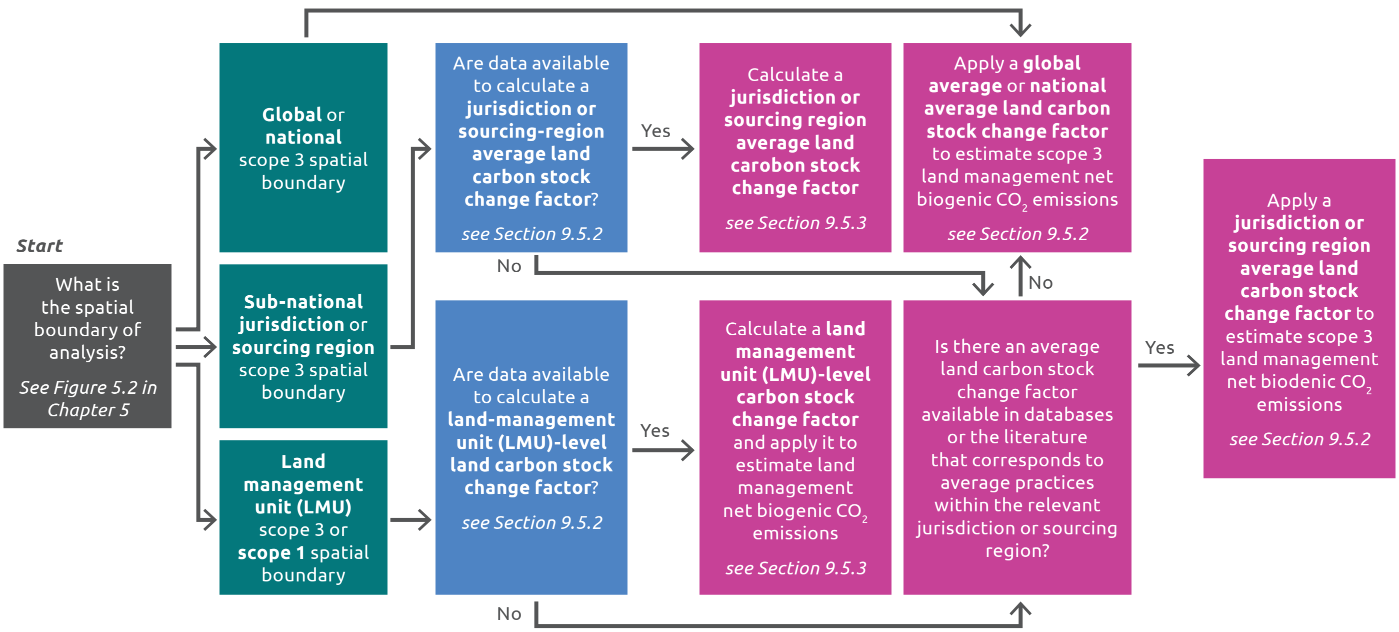
Figure 9.2 Overview of Section 9.5

Section 9.5.1 Choosing a land carbon stock change factor	→	Section 9.5.2 Data for land management net biogenic CO_2 emissions calculation approaches	→	Section 9.5.3 and 9.5.4 Calculating land management net biogenic CO_2 emissions and gross biogenic land CO_2 emissions, respectively
How does my company select or calculate an appropriate land carbon stock change factor?		What data are needed to operationalize the calculation approach?		What equations are used to perform the relevant calculations?

9.5.1 Choosing a land carbon stock change factor

Figure 9.3 provides a decision tree to assist companies in selecting and/or calculating a land carbon stock change factor to complete the accounting for land management net biogenic CO_2 emissions. For example, a company with limited traceability for the wheat it sources (i.e., applying a global or national scope 3 spatial boundary) could select a global or national carbon stock change factor representing the average annual net land carbon stock change across all wheat farms within that boundary. A company that has farm-level physical traceability for a given volume of the wheat it sources and data to estimate land carbon stock changes on those specific farms (e.g., using models calibrated using land carbon stock data from those farms and/or representative of those farms) can use such data to calculate annual net land carbon stock changes on that specific set of wheat farms.

Figure 9.3 Decision tree for choosing a carbon stock change factor to account for land management net biogenic CO_2 emissions



9.5.2 Data for land management net biogenic CO_2 emissions calculation approaches

Estimating net land carbon stock change to account for land management net biogenic CO_2 emissions can require different data inputs, depending on the relevant land use, carbon pools, and the calculation approach that is applied. When companies have limited traceability, they can utilize average land carbon stock change factors for agricultural products relevant to their supply chain based on global, country-level, or subnational jurisdiction-level factors. If net land carbon stocks are decreasing (i.e., the carbon stock change factor is less than zero), companies are required to report land management net biogenic CO_2 emissions. If net land carbon stock change is zero or increasing (i.e., the carbon stock change factor is greater than zero), companies may choose to report zero land management net CO_2 emissions or may choose to quantify and report land management CO_2 removals, if the relevant land management CO_2 removals requirements are met (see Chapters 12 and 13). Where companies have greater traceability and data availability, they can select or calculate the net land carbon stock change within the relevant spatial boundary using more specific data, e.g., by utilizing direct measurements, calibrated models, or hybrid approaches for specific sourcing regions or LMUs (see Section 9.5.3).

When selecting a land carbon stock change factor (e.g., from an LCA database) to account for scope 1 and scope 3 land management net biogenic CO_2 emissions, companies should be aware of what land-based carbon pools are included or excluded in the land carbon stock change factor to ensure complete and accurate accounting. Section 9.4.2 summarizes which carbon pools must be included, at a minimum, when estimating the net land carbon stock change for different land uses and/or product types associated with the reporting company's operations or value chain.

9.5.3 Calculating land management net biogenic CO_2 emissions

This section provides calculation guidance to calculate scope 1 and scope 3 land management net biogenic CO_2 emissions across all land-based carbon pools, including:

- Biomass carbon stock change (Section 9.5.3.2)
- Dead organic matter carbon stock change (Section 9.5.3.3)
- Soil carbon stock change (Section 9.5.3.4)

General calculation guidance that applies to estimating carbon stock changes across all land-based carbon pools is provided in Section 9.5.3.1. A general overview of the steps to calculate land management net biogenic CO_2 emissions on agricultural land is provided in Table 9.3. This general workflow applies to any of the calculation approaches in Table 9.4. Specific calculation guidance for optionally calculating *gross* biogenic land CO_2 emissions is provided in Section 9.5.4.

Table 9.3 General steps to calculate land management net biogenic CO_2 emissions on agricultural land

Step	References
Step 1: Determine the spatial boundary and monitoring frequency	Sections 9.4.3, 9.4.4, 5.4.2
Step 2: Select or calculate the carbon stock change factor(s)	Sections 9.5.2, 9.5.3, Figure 9.2
Step 3: Select a calculation approach	Section 9.5.3.1, Table 9.4, Section 6.4.3
Step 4: Calculate total land management net biogenic CO_2 emissions	Equation 9.1, Equation 9.2, 9.5.3.1–9.5.3.4
Step 5 (if applicable): Allocate emissions across outputs of the cropping system	Section 6.4.5
Step 6 (if applicable): Allocate emissions to co-products or by-products	Section 6.4.5

9.5.3.1 Overview of calculation approaches for carbon stock changes

This section provides general calculation guidance that applies to calculating land carbon stocks across all land-based carbon pools. Calculating net land carbon stock changes using the stock change accounting approach (see Section 9.4.2) is operationalized using either the Stock-Difference Method (Equation 9.1) or the Gain-Loss Method (Equation 9.2). The net land carbon stock change can be estimated for a series of different land strata that exist within the relevant assessment area. Each stratum should be defined based on similar characteristics influencing the carbon stock on lands within each stratum (e.g., climate, ecological zone, land use, management practices, soil type, etc.).

STOCK-DIFFERENCE METHOD

The Stock-Difference Method quantifies net land carbon stock change based on the annual average difference between total carbon stocks across land-based carbon pools (i.e., above-ground biomass, below-ground biomass, dead organic matter, and soil carbon pools) at two points in time, as shown in Equation 9.1.

Equation 9.1 Stock-Difference Method for net land carbon stock changes

$$\Delta C_{l,a} = \frac{C_{l,a,y_f} - C_{l,a,y_i}}{Y_f - Y_i}$$

Description		Unit	Source
$\Delta C_{l,a}$	Net land carbon stock change across all land-based carbon pools, in land stratum *l*, in assessment area *a*, between year Y_i and Y_f	tonnes C (year)$^{-1}$	Calculated
C_{l,a,y_f}	Total land carbon stock in stratum *l* in assessment area *a*, in the final assessment year Y_f	tonnes C	User input
C_{l,a,y_i}	Total land carbon stock in stratum *l* in assessment area *a*, in the initial assessment year Y_i	tonnes C	User input
Y_i	Year of initial assessment	year	User input
Y_f	Year of final assessment	year	User input
a	Assessment area		User input
l	Land stratum		User input
y_i	Year of initial assessment		User input
y_f	Year of final assessment		User input

GAIN-LOSS METHOD

The Gain-Loss Method quantifies the net land carbon stock change based on the difference between carbon gains (i.e., gross CO_2 removals and other non-atmospheric C inputs to land-based carbon pools) and carbon losses (i.e., gross CO_2 emissions and other C transfers from land-based carbon pools) in a given year, as shown in Equation 9.2.

Equation 9.2 Gain-Loss Method for net land carbon stock changes

$$\Delta C_{l,a,y} = G_{l,a,y} - L_{l,a,y} = \left(\Delta CG\_L_{l,a,y} + \Delta CG\_I_{l,a,y}\right) - \left(\Delta CL\_L_{l,a,y} + \Delta CL\_T_{l,a,y}\right)$$

Description		Unit	Source
$\Delta C_{l,a,y}$	Net land carbon stock change across all land-based carbon pools in land stratum *l*, in assessment area *a*, in year *y*	tonnes C $(year)^{-1}$	Calculated
$G_{l,a,y}$	Annual land carbon stock gains in land stratum *l*, in area *a*, in year *y*	tonnes C $(year)^{-1}$	User input
$L_{l,a,y}$	Annual land carbon stock losses in land stratum *l*, in assessment area *a*, in year *y*	tonnes C $(year)^{-1}$	User input
$\Delta CG\_L_{l,a,y}$	Annual land (L) carbon stock gains to biomass, dead organic matter, and soil carbon pools in land stratum *l*, in assessment area *a*, in year *y*	tonnes C $(year)^{-1}$	See Equation 13.1 for biomass gains; see Sections 9.5.3.3 and 9.5.3.4 for DOM and soil carbon stocks, respectively.
$\Delta CG\_I_{l,a,y}$	Annual land carbon stock gains from biogenic C inputs (I) to land stratum *l*, in assessment area *a*, in year *y*	tonnes C $(year)^{-1}$	User input
$\Delta CG\_L_{l,a,y}$	Annual land (L) carbon stock losses from biomass, dead organic matter, and soil carbon pools in land stratum *l*, in assessment area *a*, in year *y*	tonnes C $(year)^{-1}$	See Equation 9.3 for biomass losses, see Sections 9.5.3.3 and 9.5.3.4 for DOM and soil carbon stocks, respectively.
$\Delta CG\_T_{l,a,y}$	Annual land carbon stock losses due to harvested carbon and other carbon transfers (T) from land stratum *l*, in assessment area *a*, in year *y*	tonnes C $(year)^{-1}$	User input
a	Assessment area		User input
l	Land stratum		User input
y	Reporting year		User input

As shown in Equation 9.2, annual land carbon stock gains ($G_{l,a,y}$) include biomass growth through photosynthesis associated with gross biogenic land CO_2 removals, and may include gains to dead organic matter and soil carbon pools as well as other biogenic C inputs to land-based carbon pools (e.g., biochar soil amendments). Land carbon stock losses ($L_{l,a,y}$) consist of gross losses from land carbon pools to the atmosphere, including losses from biomass, dead organic matter, and soil carbon pools, and other transfers of carbon from land-based carbon pools to product or waste carbon pools (e.g., the harvest of crop biomass). Gross losses from land carbon pools to the atmosphere are also associated with gross biogenic land CO_2 emissions and include emissions from mortality, disturbances, and biomass burning of land-based carbon pools. Other transfers of carbon from land-based carbon pools are primarily the result of biomass harvests, but may also include the collection of agricultural residues and other carbon losses due to thinning, pruning, or related land management practices where carbon is taken off the land, entering the product carbon pool.

OVERVIEW OF CALCULATION APPROACHES FOR CARBON STOCK CHANGES

There are four general calculation approaches that can be used to calculate net land carbon stock changes. Hybrid approaches are also possible, which combine any of these four approaches. Under certain circumstances, when land management practices have minimal impacts on carbon stocks or annual changes in carbon stocks, companies may also assume no carbon stock change for a given land-based carbon pool. An overview of each general calculation approach is discussed below. Discussion of how each calculation approach can be applied to account for carbon stock changes across individual land-based carbon pools is provided in Sections 9.5.3.2–9.5.3.4.

Calculation approaches involve different levels of methodological complexity and calibration (Table 9.4). In general, more sophisticated methods can produce more accurate results. The IPCC's *Guidelines for National GHG Inventories* (IPCC 2006) define methodological "Tiers" which categorize calculation approaches by their relative level of methodological complexity, data requirements, and accuracy.

Factor-based approaches can be classified as Tier 1, 2, or 3 based on the data used, ranging from IPCC global default factors and country-specific or management-specific factors to factors developed using primary data from specific producers in a company's value chain. Remote sensing-based approaches can be classified as Tier 2 or Tier 3 depending on whether the approach uses regional average carbon stock estimates to estimate average carbon stock changes or directly measures carbon stock change (e.g., on a specific LMU or set of LMUs). Model-based or measurement-based approaches typically present the greatest methodological complexity and are considered Tier 3 approaches. Remote sensing, modelling, and ground measurements combined in a hybrid approach can also deliver accurate results with reduced uncertainty, though hybrid approaches can require substantial development time and calibration to deploy across all relevant geographies, land uses, carbon pools, and so on. See Section 6.4.3.1 for general discussion on the IPCC methodological "Tier" classification system.

Table 9.4 Overview of land carbon stock change calculation approaches

Calculation approach	Description of calculation approach	Methodological complexity
Factor-based approach	Methods that multiply activity data by an emissions factor or carbon stock change factor to determine emissions, removals, or other accounting category values for a given process	Tier 1, 2, or 3
Model-based approach	Methods that use mathematical modelling techniques to estimate emissions, removals, or carbon stock changes using input variables and fixed parameters calibrated to the specific model applications	Tier 3
Remote sensing-based approach	Methods that use satellite or aerial information to collect activity data (e.g., plantings or harvests) on the land to estimate emissions, removals, or carbon stock changes	Tier 2 or 3
Measurement-based approach	Methods that directly quantify GHG emissions, removals, or associated carbon stock changes, using direct measurement of GHG pools and fluxes	Tier 3
Hybrid calculation approach	A combination of methods that involves both calculation and direct measurement approaches	Variable
Assume no carbon stock change	Under certain circumstances, companies may assume no carbon stock change when land management practices have minimal impacts on carbon stocks or annual changes in carbon stocks	Tier 1

FACTOR-BASED CALCULATION APPROACHES

Where data are unavailable for the specific lands or land management practices impacting carbon stock changes in a given spatial boundary, factor-based methods can be applied to estimate annual net land carbon stock changes. These methods use activity data on land area and management practices stratified by environmental factors (e.g., climate, ecological zone, soil type, etc.) and land management practices (e.g., land use, soil management practices, livestock management practices, etc.). Activity data related to management practices and land areas within a given stratum in the relevant spatial boundary are then multiplied by a corresponding carbon stock change factor or emission factor to calculate total net carbon stock changes.

Factor-based approaches generally rely on secondary data, which reduces the accuracy of estimates relative to other calculation approaches. For example, carbon stock change factors may represent global average IPCC default values or average values by country and management practice. Increased resolution of stratification in the assessment (e.g., based on more detailed soil, vegetation, or management types, etc.) and corresponding carbon stock change factors can be used to improve the accuracy and precision of carbon stock change estimates. Note that factor-based approaches using secondary data do not meet the requirements for accounting for and reporting land management CO_2 removals in this *Standard* (see Chapters 12 and 13).

Many off-the-shelf GHG accounting tools use factor-based approaches, which can be useful when developing initial estimates of carbon stock changes, to understand the relative magnitude of changes, and to estimate uncertainty. These estimates can then help to prioritize primary data collection efforts to support more refined estimates of carbon stock changes due to specific land management practices.

MODEL-BASED CALCULATION APPROACHES

Model-based approaches use mathematical relationships between multiple input variables (e.g., temperature, precipitation, vegetation type, management practices, etc.) and fixed parameters (i.e., calibration factors) to estimate annual net land carbon stock changes across land-based carbon pools. When evaluating and selecting a model to estimate land carbon stock changes, evidence should be provided that the underlying data and assumptions of the model are appropriate for the relevant area of analysis within a given spatial boundary (e.g., model parameters fall within uncertainty ranges in peer-reviewed literature), the model predictions are more accurate than the results derived from factor-based calculation approaches (e.g., disclosing statistical accuracy metrics pertaining to model validation), and the predicted values do not fall outside the uncertainty ranges provided by IPCC Tier 1 estimates.

Empirical models use field measurements to establish statistical relationships between GHG fluxes and agricultural management factors. Process-based (or mechanistic) models mathematically describe biogeochemical processes that control the production, consumption, and emission of GHGs. Some models may only require one or several input variables to estimate GHG fluxes; others may have extensive data requirements that span different spatial and temporal scales. Common input data include physical variables (e.g., temperature, precipitation, elevation, and soil nutrient levels) or biological variables (e.g., plant diversity and soil microbial activity).

Model accuracy is variable and depends on the robustness of the model, calibration of the fixed parameters to the particular application, and the accuracy of the input variables. For example, if a model is applied in a new agro-climate regime for which it was not previously calibrated, the modelling results may not be reliable. Companies that use model-based approaches to estimate annual (or annualized) net land carbon stock changes should report the uncertainty range and regularly update the model based on resampling of measured land carbon stock changes, at a minimum every five years. This resampling frequency is required if companies use such estimates to account for land management CO_2 removals (see Requirement 21.LMR).

REMOTE SENSING-BASED CALCULATION APPROACHES

Remote sensing-based approaches can be considered a subset of model-based approaches in which remote sensing data (as opposed to data gathered via operations or field measurements) are used to inform model predictions of annual net land carbon stock changes. Different types of remote sensing data are available to detect land management practices, carbon stocks, carbon stock changes, or all of the above. Optical data from multispectral or hyperspectral imagery, as well as data from active sensors that emit a signal to gather information (such as light detection and ranging [LiDAR] and radio detection and ranging [radar]), can be used to support remote sensing-based approaches to estimate land-based carbon stocks at a point in time. Remote sensing technology can effectively cover much larger areas in comparison to measurement-based methods. However, local calibration and/or model development is still required to increase accuracy and reduce uncertainties associated with predictions from remotely sensed data.

Optical remote sensing data can suffer from saturation at high biomass levels (see Box 9.4) and should be combined with other data, such as bioclimatic data, stand age, or forest inventory data, to improve the predictive capacity. Remote sensing approaches pose more challenges when applied to estimate soil carbon stock changes, but can be useful to provide information about the cropping systems, tillage, and residue management practices as inputs to model-based approaches. Data from active remote sensing can produce more accurate predictions of carbon stock changes, but this type of data is generally more expensive to collect and requires a high level of skill and knowledge to pre-process, remove noise, and process the information.

MEASUREMENT-BASED CALCULATION APPROACHES

Repeated measurement of carbon stocks in land-based carbon pools within a given stratum can provide the most accurate estimates of annual net land carbon stock changes, depending on the sampling methods, protocols, or other inventory methods used. Measurement-based approaches are typically used to estimate carbon stocks based on sampling within a given stratum that represents a relatively homogeneous land area with respect to both the natural and management factors that impact carbon stocks. The number of sampling plots within a stratum and the frequency of resampling plots can be determined based on the expected variance in carbon stocks within the stratum, the expected magnitude of carbon stock changes, and the desired precision in the estimates.[3] Measurements should occur at similar times during the year to account for seasonal changes in carbon stocks and ensure consistency in the measurements over time. Sampling protocols will vary depending on the land use and carbon pool; common methods for collecting field data across land-based carbon pools are described in Sections 9.5.3.2–9.5.3.4. Measurement-based approaches can be labor-intensive and expensive, but when combined with model-based approaches across a well-designed land stratification and sampling protocol, they can allow for increased scalability.

When calculating scope 1 land management net biogenic CO_2 emissions using a measurement-based calculation approach, all lands under the company's ownership and control should be stratified, and sampling should occur across all lands in each stratum. For scope 3 calculations, measurements should be taken on a subset of lands in the value chain that are representative of lands included in the relevant scope 3 spatial boundary, as determined in accordance with the requirements and guidance in Chapter 5.

HYBRID APPROACHES

In practice, the individual calculation approaches described above are often combined to estimate land carbon stock changes. There is an increasing number of public and proprietary tools (e.g., calculation spreadsheets, software, and protocols) available to estimate land carbon stock changes that combine elements of factor-based, remote sensing-based, and model-based calculation approaches.

Off-the-shelf tools designed to be accessible to a relatively non-technical user tend to implement Tier 1 or Tier 2 approaches. In general, this *Guidance* does not recommend specific tools for calculating land management net biogenic CO_2 emissions and other accounting categories. A company should evaluate and select tools using the guidance presented in Section 6.4. Tools must also conform to the accounting and reporting principles and relevant requirements in this *Standard*.

ASSUME NO CARBON STOCK CHANGE

The carbon stocks of a given land-based carbon pool might not be directly impacted by management activities or might not significantly change from year to year. IPCC national GHG inventory guidelines provide conservative guidance for when the assumption of no change in carbon stocks can be applied for a particular land use and carbon pool. Sections 9.5.3.2–9.5.3.4 below provide guidance for when the assumption of no carbon stock change may be applied when accounting for carbon stock changes across different land-based carbon pools.

9.5.3.2 Calculating biomass carbon stock change

The biomass carbon pool includes carbon in live above-ground and below-ground biomass carbon pools. Biomass carbon stocks change due to impacts from continuous processes (e.g., growth, change in vegetation development stage, decomposition, etc.) and discrete events (e.g., management practice change; disturbance due to fire, harvest, pest and disease outbreaks; land use change, etc.). Continuous processes tend to affect biomass carbon stocks over broader areas, whereas discrete events impact specific areas.

As set forth in Requirement 14, when estimating net land carbon stock change, companies must include carbon stock changes, at a minimum, in above-ground and below-ground biomass carbon pools on all:

- Forest lands; and
- Grasslands, croplands, wetlands, and/or settlements with woody or permanent cover

If companies do not choose to account for and report "land management CO_2 removals" attributable to biomass carbon stock changes, then accounting for "land management net biogenic CO_2 emissions" may follow the Tier 1 or Tier 2 guidelines below for calculating biomass net carbon stock changes using a factor-based calculation approach (e.g., the Gain-Loss Method with IPCC default factors), or assuming no biomass carbon stock change, when appropriate (see "Assume no biomass carbon stock change" subsection below).

When companies seek to account for and report "land management CO_2 removals" associated with net increases in biomass carbon stocks, accounting should follow the Tier 3 measurement and modeling guidance below, as well as meet the removals requirements set forth in Chapters 12 and 13.

FACTOR-BASED APPROACHES TO CALCULATE BIOMASS CARBON STOCK CHANGES

Companies can apply factor-based methods to estimate biomass carbon stock changes resulting from land management practices using either the Gain-Loss or Stock-Difference Methods (see Equations 9.1 and 9.2 in Section 9.5.3.1). Activity data on the total land area stratified by land use, climate, ecological zone, and management or disturbance type can be combined with IPCC Tier 1 or country-specific carbon stock growth and loss factors to estimate biomass carbon stock gains or losses using the Gain-Loss Method. To operationalize the Stock-Difference Method at the sub-national, sourcing region, or land management unit level, Tier 3 remote sensing-based, model-based, measurement-based, or hybrid approaches are recommended.

Activity data on perennial woody crops (e.g., in perennial cropland monocultures or agroforestry systems), as well as areas experiencing disturbance events, are needed to estimate biomass losses using IPCC Tier 1 or country-specific carbon stock loss factors.

Factor-based data on land use stratified by forest types are typically insufficient to estimate carbon stock changes using the Stock-Difference Method based on Tier 1 data alone. Estimates of net land carbon stock should be based on repeated inventory plot measurements or another sampling protocol with a sufficient number of plots or samples to achieve a given level of precision at a given confidence level (e.g., within 20 percent of the mean at a 95 percent confidence interval), as described in the measurement-based approaches section below.

REMOTE SENSING-BASED APPROACHES TO CALCULATE BIOMASS CARBON STOCK CHANGES

Remote sensing technology (i.e., satellite and aerial technology) can effectively cover much larger areas compared to field measurement-based methods. Different types of remote sensing data are available to detect and quantify above-ground biomass, including multispectral or hyperspectral data, as well as data from active sensors such as LiDAR and radar. Local calibration and/or model development is required to derive above-ground biomass, and/or above-ground biomass change, from the remotely sensed data. In general, estimating biomass carbon stock changes via satellite remote sensing is useful primarily for capturing relatively large and abrupt carbon stock losses (e.g., deforestation). In the absence of repeated and detailed airborne or terrestrial LiDAR campaigns, it is more difficult to capture with satellite data less intensive carbon stock degradation processes and a relatively gradual increase in biomass carbon stocks over time in areas with moderate to high biomass carbon stocks. However, continued research may enable direct biomass measurements from satellite data; Box 9.4 provides additional discussion of remote sensing technologies.

Box 9.4 Remote sensing technologies for detecting biomass carbon stock changes

Technology for biomass remote sensing can be broadly classified as optical remote sensing or active remote sensing, as discussed below:

- **Optical remote sensing**: This technology uses natural radiation from the sun to provide a two-dimensional view of vegetation and other surface features. This technology is easily accessible and affordable. Its main limitation is rapid saturation with forest biomass, as the reflectance signal in visible and near infrared spectra is mostly correlated with the green leaf area index (LAI) and vegetation canopy cover, which saturates around an LAI of 3 to 4 m^2 $(m^2)^{-1}$. In addition, wood biomass becomes decoupled from LAI after a given stand age, as wood biomass continues to increase after canopy closure. Thus, a direct relationship between spectral reflectance and forest biomass can only be observed where LAI is low. In natural forests, this complexity is increased due to species and age mixtures, resulting in complex forest stand structures. Optical remote sensing data must be combined with other data, such as bioclimatic data, stand age, or forest inventory data, to improve the biomass predictive capacity. Variable atmospheric conditions in time and space, topographic factors (slope and aspect), and the sensor angle in relation to the angle of the sun can affect vegetation reflectance and the resulting relationships between reflectance and above-ground biomass. Therefore, optical remote sensing data should be combined with other data, such as LiDAR, bioclimatic data, stand age, or forest inventory data, to improve biomass predictive capacity.
- **Active remote sensing**: LiDAR and radar technologies are presently the most promising techniques for forest biomass estimation, as they penetrate through vegetation and thus provide additional information related to vegetation height and structure. Radar backscatter in the P and L bands is highly correlated with major forest parameters such as tree age, tree height, diameter at breast height (DBH), basal area, and above-ground biomass. The saturation problem described above is also common in radar data and depends on the wavelengths, polarization, and the characteristics of the vegetation stand structure and ground conditions. One benefit of LiDAR and radar data is that they are less affected by cloud conditions (e.g., in tropical regions). LiDAR data can also be acquired during both day and night, as it is independent of light intensity. Airborne LiDAR data are generally more expensive to collect and require a high level of skill and knowledge to pre-process, remove noise, and process the information into a final product. While having coarser spatial resolution than airborne data, satellite-based LiDAR data and related biomass products may provide a more cost-effective option for above-ground biomass quantification and validation (Duncanson et al. 2022).

MODEL-BASED APPROACHES TO CALCULATE BIOMASS CARBON STOCK CHANGES

Modeling biomass carbon stock changes can help improve annual estimates when biomass inventories are conducted at monitoring frequencies below once per year. Available models are designed to be applied at different scales of analysis: local forest growth and yield models can be used to project stand-level dynamics, while global vegetation models are used to develop national or regional estimates of biomass carbon stock changes.

When selecting models, companies should consider a range of factors, including the relevance of the model to the specific land use, geography, or management practices; data availability both for input variables and calibrating the model; the ability to perform and report uncertainty analysis; the technical capacity to run the model; and the quality assurance and quality control procedures needed to document and report model results. As set forth in Section 6.3, companies should calibrate model-based calculation approaches using empirical data specific to the land area, management practices, and GHG impacts (i.e., carbon stock changes or GHG emissions) under analysis, at a minimum every five years. The calibration of biomass models should be based on local or regional inventories or other direct sampling approaches, as described in the measurement-based approaches below. Note that, when accounting for and reporting land management CO_2 removals, model-based and remote sensing-based approaches must be recalibrated at least every five years, as set forth in Requirement 21.LMR (see Chapter 13).

MEASUREMENT-BASED APPROACHES TO CALCULATE BIOMASS CARBON STOCKS AND CARBON STOCK CHANGES

Biomass carbon stock changes can be measured through the resampling of field plots in a particular stratum or through comprehensive inventory methods. When applied in an inventory context, measurements should begin in the base year or base period, and consistent methods should be applied when resampling recurs over time.

Biomass carbon stocks can be measured through the use of either on-the-ground measurements of tree diameter and height or destructive biomass sampling techniques (see Box 9.5). When using measurement-based approaches on particular lands or strata, companies should refer to peer-reviewed publications or protocols that provide allometric equations, inventory methods, or destructive biomass sampling protocols for measuring biomass carbon stock on those relevant lands or strata.[4] Inventory methods or other sampling protocols should specify which components of above-ground biomass (e.g., above-ground live tree biomass, herbaceous biomass) and below-ground biomass (e.g., coarse root biomass, fine root biomass) are included in the biomass carbon stock estimates. Companies should justify any exclusions when estimating biomass carbon stocks using measurement-based approaches.

Box 9.5 Direct measurement of biomass carbon stocks

- **Above-ground live tree biomass**: The above-ground biomass carbon pool includes the carbon in terrestrial living vegetation, both woody and herbaceous, above the soil, including stems, stumps, branches, bark, seeds, and foliage. Above-ground live tree biomass includes biomass with a woody stem diameter size that exceeds a specified threshold (e.g., ≥5 cm diameter). Above-ground live tree biomass is typically estimated using field measurements of tree diameter and height together with allometric equations. Allometric equations are empirical models used to estimate physical properties (e.g., total biomass) using non-destructive measurements of biomass characteristics.

  Allometric equations are developed through destructive sampling of biomass in the tree or shrub trunk, branches, twigs, and foliage across a representative sample of individual trees or shrubs (Roxburgh et al. 2015). The most commonly used independent variable in allometric equations is diameter at breast height (which, for most countries, is measured at 1.3 m from the soil surface). Allometric equations may also require additional field measurements, such as tree canopy height and wood density, or provide alternative guidance on measuring trunk diameter based on the vegetation type.

- **Herbaceous biomass**: Herbaceous biomass includes non-woody vegetation such as crops, grasses, sedges, forbs, or vines, as well as plants with a woody stem diameter below the threshold specified for above-ground live tree biomass (e.g., <5 cm), unless otherwise specified. Herbaceous biomass can significantly contribute to the carbon stocks of grasslands and croplands as well as certain forest types.

  Herbaceous biomass carbon stocks can be sampled through destructive sampling within representative plots or subplots. Plots are typically sampled within two weeks of peak biomass for the vegetation type, where all herbaceous biomass is clipped within the plot or along a strip, depending on the protocol. Herbaceous biomass is then dried to determine the total dry weight of above-ground biomass recovered, as well as the measurement of carbon content of biomass using elemental analyzers.

- **Below-ground biomass**: Below-ground biomass includes root diameter size classes ≥2 mm, unless otherwise specified. Estimates of below-ground biomass and carbon stocks are often determined based on the above-ground biomass estimates for a given vegetation type. Allometric equations used to estimate below-ground biomass based on above-ground biomass (i.e., root-to-shoot ratios) can be developed based on destructive sampling techniques.

  Destructive sampling of root biomass is labor-intensive, requiring sampling below-ground biomass by taking multiple soil cores within plots or subplots to a minimum depth of 20 cm to 1 m, depending on the ecosystem and vegetation type. Soil samples are then commonly sieved to separate coarse roots (typically defined as ≥2 mm) and fine root fragments (<2 mm). Root biomass is then dried to determine the total dry weight of root biomass recovered, as well as the measurement of carbon content of root biomass using elemental analyzers (Mokany et al. 2006).

ASSUME NO BIOMASS CARBON STOCK CHANGE

When land management practices have minimal impacts on biomass carbon stocks or annual changes in biomass carbon stocks, companies may apply an assumption of no biomass carbon stock change. Companies may assume no biomass carbon stock change on land under the following land uses and conditions:

- Croplands with temporary, non-woody biomass cover (e.g., annual row crops) where there is no conversion between land uses, where the land has been under cultivation for at least 20 years, and where no management practice changes that have the potential to impact biomass carbon have occurred in the reporting year.
- Grasslands with temporary, non-woody cover (e.g., pastures without trees) where there is no conversion between land uses, where the land has been grazed for at least 20 years, and where no management practice changes have occurred in the reporting year.
- Settlements where there is no conversion of land from other uses or between land uses, and where no management practice changes to land containing woody biomass have occurred in the reporting year.
- Other lands where there is no conversion of land from other uses.

Companies assuming no change in biomass carbon stocks in the reporting year should demonstrate that no land management activities that have the potential to impact biomass carbon are occurring in the reporting year on relevant lands. If any land management activities may impact biomass carbon, then companies should collect the necessary data to account for biomass carbon stock change. Examples of such activities include, but are not limited to:

- Permanent land management changes on croplands (e.g., changes in crop rotation, irrigation, or nutrient management, etc.) that have persisted for at least three years prior to the reporting year.
- Management activities that may significantly impact biomass carbon stocks on croplands, including woody biomass removals, site preparation, and prescribed fires.
- Significant modification of grazing intensity occurring on pasture and grazing land that has persisted for at least three years prior to the reporting year.
- Management activities that may significantly impact biomass carbon stocks on grasslands, including woody biomass removals, site preparation, and prescribed fires.
- Management activities that may significantly impact biomass carbon stocks on settlement lands, including changes in land uses within settlements, tree planning and pruning, and changes in landscape management.
- Management activities on other lands that may significantly impact biomass carbon stocks, including changes in land uses within other lands.

9.5.3.3 Calculating dead organic matter carbon stock change

The dead organic matter (DOM) carbon pool consists of the carbon in dead wood and litter carbon pools. The dead wood pool includes standing dead trees, downed woody debris, forestry residues, dead coarse roots, and other dead organic material larger than or equal to 10 cm in diameter, unless otherwise specified. The litter pool includes all non-living biomass less than the diameter threshold for dead wood but greater than the 2 mm threshold for soil organic matter, including litter and agricultural residues.

DOM carbon stocks can be impacted by management decisions (e.g., agricultural residue management practices) or non-anthropogenic factors such as natural disturbances or temperature and precipitation changes that impact decay rates.

As set forth in Requirement 14, companies are, at a minimum, required to account for DOM net carbon stock changes and the associated land management net biogenic CO_2 emissions where management practices significantly impact DOM. For scope 1 and scope 3 accounting, companies that own or control the following lands, or that have them in their value chains, must account for and report DOM net carbon stock changes on:

- Forest lands where management practices significantly impact forestry residues or dead wood
- Grasslands where management practices significantly impact residues or dead wood
- Croplands where management practices significantly impact agricultural residues

FACTOR-BASED METHODS TO CALCULATE DOM CARBON STOCK CHANGES

Companies can apply factor-based methods to estimate DOM carbon stock changes resulting from land management practices using either the Stock-Difference or Gain-Loss Methods (see Equations 9.1 and 9.2 in Section 9.5.3.1). Activity data on the total land area, stratified by land use, climate, ecological zone, and management or disturbance type, can be combined with Tier 1 or country-specific DOM carbon stock change factors to estimate DOM carbon stock gains or losses.

Since the Tier 1 method assumes no net changes in DOM carbon stocks and Tier 2 methods use national data, these factor-based approaches do not meet the criteria for accounting for and reporting CO_2 removals in corporate GHG inventories for lands where management practices significantly impact DOM. Tier 3 methods are data-intensive and require field measurement and modeling to estimate the carbon stock changes in DOM, as explained in the following sections.

To calculate the change in DOM carbon stocks using either the Stock-Difference or Gain-Loss methods requires activity data on the area of attributable productive lands, which are multiplied by a DOM carbon stock change factor. The Gain-Loss method estimates DOM carbon stock changes based on the difference between inputs to, and losses from, the dead wood and litter carbon pools. This approach requires data regarding annual carbon additions into the DOM carbon pool from stem mortality and litterfall, and turnover and losses from the DOM carbon pool due to decomposition rates. Estimating DOM carbon stock changes using the Stock-Difference Method requires estimates of the dead wood and litter carbon stock at two different points in time. The annual carbon stock change is calculated as the difference between two estimates of dead wood and litter carbon stock, divided by the time period between the two measurements.

REMOTE SENSING-BASED APPROACHES TO CALCULATE DOM CARBON STOCK CHANGES

Remote sensing technology for estimating DOM carbon stock changes remains limited, though research is underway to use optical remote sensing to identify and map coarse and large woody debris. Using optical remote sensing to identify coarse woody debris is limited by tree canopy and understory cover, since these features conceal the extent of coarse woody debris on the forest floor. The use of aerial imagery in riparian areas with low vegetation coverage in post-disturbance situations (e.g., fires, hurricanes) shows promising results in detecting coarse woody debris.

LiDAR is capable of providing more complete forest structural information. This technology is valuable for coarse woody debris assessment, especially in areas with high vegetation coverage, though the technology is more limited in its spatial coverage. The combination of aerial imagery, LiDAR, and multispectral LiDAR may provide increased accuracy and spatial coverage.

MEASUREMENT-BASED APPROACHES TO CALCULATE DOM CARBON STOCKS AND CARBON STOCK CHANGES

Repeated field measurements of DOM carbon stock changes over time are both labor- and time-intensive, especially when sampling over large areas or numerous strata. Box 9.6 discusses direct measurement approaches for DOM carbon stocks.

Box 9.6 Direct measurement of dead organic matter carbon stocks

Methods of sampling dead organic matter vary by country but typically include separate methodologies for estimating standing dead trees, downed woody debris, and litter (Woodall et al. 2009). The following methods can be used to estimate DOM carbon stocks for a single point in time, including carbon stocks in standing dead trees, dead woody debris, and litter.

Standing dead tree biomass: In the field, standing dead trees can be classified into decay classes that can be used in the calculation of dead tree biomass, such as the example below from the United States Forest Service (USFS 2024):

- Decay class 1: All branches and limbs are retained; resembles a live tree except for the absence of leaves
- Decay class 2: Few limbs, no fine branches; top may be broken
- Decay class 3: Limb stubs only; top is broken
- Decay class 4: Few or no stubs; advanced decay at the base
- Decay class 5: No limbs, branches, or stubs; less than 20 percent of bark remaining

The volume and carbon stock values of standing dead trees can be estimated using similar methods to those of standing live biomass, described above in Box 9.5. When allometric equations are applied, they should be specific to tree species and disturbance types, where possible, and appropriately factor in biomass reductions and the decay class of the standing dead trees.

Downed woody debris: Downed woody debris includes dead woody biomass of a diameter size class ≥10 cm, unless otherwise specified. There are two main methodologies to estimate downed woody debris from field measurements: plot-based and line-intersect methods.

- **Plot-based method**: The downed woody volume is calculated by measuring the length and the diameter at both ends of woody debris located in the plot (Ståhl et al. 2001).
- **Planar intersect method**: This method counts woody debris intersected along several installed transects within a plot. The woody debris crossing the transect is separated into different diameter classes (Brown 1971). The length of a transect can vary from 10 to 20 m depending on the woody debris abundance.

Litter: Litter is defined as the surface detritus and particulate organic matter (diameter size classes ≥2 mm and <10 cm, unless otherwise specified) that lies above the soil surface, but excludes downed woody debris. Forest floor litter consists of fallen leaves, seeds, fruit, bark fragments, and small pieces of wood. In the field, litter biomass is calculated by harvesting and weighing all material located inside plots that range from 25 × 25 cm to 50 × 50 cm.

ASSUME NO CHANGE IN DOM CARBON STOCKS

When land management practices have minimal impacts on DOM carbon stocks or annual changes in DOM carbon stocks, companies may apply an assumption of no DOM carbon stock change. Companies may assume no DOM carbon stock change on land under the following land uses and conditions:

- Croplands where there is no conversion between land uses, where the land has been under cultivation for at least 20 years, and where no residue management practice changes that have the potential to impact DOM carbon have occurred in the reporting year.
- Grasslands where there is no conversion between land uses, where the land has been grazed for at least 20 years, and where no residue management practice changes that have the potential to impact DOM carbon have occurred in the reporting year.
- Settlements where there is no conversion between land uses, and where no management practice changes to land containing DOM have occurred in the reporting year.
- Other lands where there is no conversion of land from other uses.

Companies assuming no change in DOM carbon stocks in their accounting must monitor land management activities with the potential to impact DOM carbon and should demonstrate that no land management activities that have the potential to impact DOM carbon are occurring in the reporting year on relevant lands. If any land management activities may impact DOM carbon, then companies should collect the necessary data to account for the DOM carbon stock change. Examples of such activities include, but are not limited to:

- Management activities on croplands that may significantly impact DOM carbon stocks, including changes in crop residue management, fuel wood removals, site preparation, and prescribed fires.
- Management activities on grasslands that may significantly impact DOM carbon stocks, including fuel wood removals, site preparation, and prescribed fires.
- Management activities on settlement lands that may significantly impact DOM carbon stocks, including changes in land uses within settlements and changes in landscape management.
- Management activities on other lands that may significantly impact DOM carbon stocks, including changes in land uses within other lands.

9.5.3.4 Calculating soil carbon stock change

The soil carbon pool includes the carbon in soil minerals (i.e., soil inorganic carbon) and soil organic matter less than 2 mm in size (i.e., soil organic carbon). The soil carbon pool can be further broken down into three sub-pools: the soil inorganic carbon pool, the mineral soil organic carbon pool, and the organic soil organic carbon pool.

Soil disturbance due to land management can result in losses of carbon as emissions from increased soil respiration and through surface erosion. Soil organic carbon (SOC) can be lost through land management activities (e.g., changes in land use, soil tillage practices, changes in vegetative carbon inputs to soils, etc.) and natural factors (e.g., temperature and/or precipitation impacting soil organic matter decay rates, etc.).

Disturbance of organic soils (e.g., peatland) can result in particularly large emissions of carbon, as these soils contain much larger soil carbon stocks than mineral soils. In general, companies should follow IPCC guidance when determining whether a soil is organic. Note that disturbed organic soils also release N_2O; these emissions, and other non-biogenic CO_2 emissions from managed soils, are accounted for in Chapter 10. Land management can also increase soil organic carbon content through increasing organic matter inputs or minimizing emissions from soil respiration. Soil inorganic carbon (SIC) cannot be built up over decadal timescales, but can be lost through land management and natural factors, principally by activities that acidify soil, leading to the loss of calcium carbonate ($CaCO_3$) (e.g., due to acid rain or through the use of ammonium-based fertilizers).

Companies are required to account for soil carbon stock changes and the associated emissions and removals for land uses where management practices may significantly impact soils. For scope 1 and scope 3 accounting, companies that own or control the following lands, or that have them in their value chains, must account for and report soil carbon stock changes:

- All croplands and grasslands; and
- Forest lands, wetlands, and settlements where management practices significantly disturb soils.

If companies do not choose to account for and report land management net CO_2 removals from soil carbon stock changes, then accounting may follow the Tier 1 or Tier 2 guidelines below for either calculating soil net carbon stock changes using factor-based methods (i.e., using IPCC default emission factors, carbon stock change factors, and reference soil carbon stocks by stratum), or assuming no soil carbon stock change.

When companies seek to account for and report land management net CO_2 removals associated with net increases in soil carbon stocks, accounting should follow the Tier 3 measurement and modeling guidance below, as well as meet the removals requirements set forth in Chapters 12 and 13.

FACTOR-BASED APPROACHES TO CALCULATE SOIL CARBON STOCK CHANGES

Companies can apply factor-based methods to estimate soil carbon stock changes resulting from land management practices using either the Stock-Difference or Gain-Loss Method (see Equations 9.1 and 9.2 in Section 9.5.3.1). Activity data on the total land area, stratified by land use, climate, ecological zone, and management or disturbance type, can be combined with Tier 1 or Tier 2 soil carbon stock change factors to estimate soil carbon stock gains or losses.[5] Factor-based methods can also be used to estimate carbon emissions from land management activities on drained or disturbed organic soils (i.e., peatlands), using IPCC emission factors.[6] Note that disturbed organic soils and peatlands also release nitrous oxide (N_2O); these emissions, and other non-biogenic CO_2 emissions from managed soils, are accounted for in Chapter 10.

Use of such factor-based methods has the advantage of being relatively simple to implement. Particularly in a scope 3 context, Tier 1 and 2 carbon stock change factors can be applied based on knowledge of the land area adopting a given management practice change on agricultural land:

- **Tier 1** soil carbon stock change factors attribute an average soil carbon gain or loss expected from agricultural management practices and can be used to estimate net soil carbon stock change on lands of a given soil type. Tier 1 factors should only be used when the scope 3 spatial boundary is set at a national jurisdiction level or broader, or no more granular data are available. When companies set a more granular scope 3 spatial boundary, and where national or subnational management-specific data are available, Tier 2 factors should be used.
- **Tier 2** soil carbon stock change factors assign a soil carbon gain or loss factor expected from agricultural management practices applied in national or subnational contexts by accounting for specific regional soil properties and conditions (e.g., weather and climate variation).

For companies that pursue Tier 2 approaches, carbon stock change factors (i.e., emission factors) should be based on peer-reviewed literature specific to the region, the production and management systems being assessed, soil types, default or reference carbon stocks, default or specified soil depth, and default or specified time dependence of the stock change factors.[7] Factors can be generated through literature review and meta-analysis of observations from research plots or from meta-modeling approaches across soil carbon models to simulate potential soil carbon changes based on a range of management assumptions for a given region. For some regions and countries, national databases and guidance on soil carbon estimation may be available. The National Inventory Report (NIR) submitted annually to the UNFCCC (Section 6.3 of the NIR)[8] may contain such information. These values are peer-reviewed and externally verified by the UNFCCC through their Expert Review Team (ERT) annually.

As set forth in Requirement 22 in the *Standard*, when accounting for and reporting carbon stock gains (i.e., land management CO_2 removals), factor-based methods must be based on empirical data specific to the sinks and pools where carbon is stored.

MODEL-BASED APPROACHES TO CALCULATE SOIL CARBON STOCK CHANGES

Process-based biophysical models of agro-ecosystems can be used to simulate changes in soil carbon stocks resulting from land management. These models account for specific field and location conditions, such as soil properties, topography, weather, and comprehensive management decisions including crop rotation, tillage intensity, irrigation, nutrient management, residue management, and other in-field practices.

Process-based models are complex and require extensive background data on environmental conditions and accurate parameterization for a given region and set of circumstances. Further, modelling requires periodic calibration against measured values and updating of supporting environmental data. Models that represent biogeochemical processes are expected to be more transferable and accurate across gradients in environmental factors compared to default (e.g., IPCC) emissions factors. Several biogeochemical models that meet IPCC Tier 3 guidelines for CO_2 emissions and removals can be used for estimating annual changes in soil carbon stocks.

For reporting land management CO_2 removals corresponding to net increases in soil carbon stocks, measurements in the base year and at five-year intervals can be complemented by the use of process-based modeling that meets IPCC Tier 3 guidelines. For example, a company seeking to report on land management CO_2 removals associated with net soil carbon stock increases could account for soil carbon stock changes by integrating model-based approaches into an ongoing storage monitoring approach, as follows:

1. Measurement of a soil carbon stock in the inventory base year or period
2. Estimation of annual soil carbon stock change using model-based approaches (in years 1–5)
3. Measurement of soil carbon stock in year 5 to determine the annualized carbon stock change and to compare against modeled results reported in years 1–5 to recalibrate if necessary
4. Ongoing monitoring of carbon stock changes, and repetition of steps two and three for each subsequent five-year interval

REMOTE SENSING-BASED APPROACHES TO CALCULATE SOIL CARBON STOCK CHANGES

Soil carbon cannot be detected directly through satellite remote sensing; however, such approaches can be used to detect changes in land cover and land management. Land cover and management data derived from remote sensing products can then be used to estimate changes in soil carbon stocks using emission factors, statistical models, or process-based models.

While land cover change remote sensing methods are relatively advanced and accessible, land management change remote sensing is primarily focused on detecting changes in crop rotation, including cover crop use, and changes in tillage intensity on agricultural lands. As such, remote sensing methods may not apply to all relevant agricultural practices. Remote sensing-derived maps of conservation practice adoption may also be useful for the verification of reported practice changes by farmers in a region.

MEASUREMENT-BASED APPROACHES TO CALCULATE SOIL CARBON STOCKS AND SOIL CARBON STOCK CHANGES

A sampling protocol can be used to measure soil carbon stock change on a select portion of the land area contributing to the overall net soil carbon stock change. Companies should follow an established sampling protocol that accounts for variation of important environmental factors and that stratifies the total land area included in the analysis to ensure that sample measurements are representative of the given spatial boundaries (see Chapter 5 for requirements and guidance on setting spatial boundaries). Soil properties and management practice changes on the sampled lands must be representative of the full land area contributing to the soil carbon stock changes (see Table 9.5). Soil carbon baseline and soil carbon change measurements should be conducted on the same lands and using the same sampling protocols (i.e., the same plots should be measured in the base year or period and the subsequent measurement years).

Table 9.5 discusses three essential components of measurement-based approaches to carbon stocks and soil carbon stock changes over time.

Table 9.5 Key components of soil carbon stock calculation using direct measurement

Key component of soil carbon stock measurement	Discussion
1. Sample design and stratification	The first step in a measurement-based approach is to determine where to collect samples and how many to collect. The sample design and size should ensure adequate power to detect statistical significance and should be consistent with land management plans to inform other soil sampling objectives (e.g., nutrient management, soil pH, soil health, or other sampling requirements specified by related GHG programs). Statistical methods like k-means clustering combined with point randomization or conditional Latin hypercube sampling can be used to generate a set of sampling points based on factors that are known to affect soil carbon, like soil mineralogy, soil texture, vegetation, and climate. It is important to follow a field sampling protocol for measuring soil carbon stocks. For instance, standard operating procedures for collecting samples for soil carbon stock quantification can be found in the Soil Health Institute's Soil Health Sampling Protocol (SHI SHS Protocol) and the FAO's Global Symposium on Soil Organic Carbon Monitoring, Reporting, and Verification Protocol (FAO GSOC-MRV Protocol).[a]
2. Bulk density and equivalent soil mass accounting methods	Bulk density (i.e., the mass of soil per volume) is necessary to calculate the soil carbon stock for a given land area or stratum. Analytical measurements provide the concentration of carbon in a sample. Multiplying concentration by bulk density gives a stock in units, such as kg C per ha, to a depth reflective of the impacts of soil tillage (which can vary from 30 to 100 cm depending on tillage practices representative of the total land area included). However, management practices can impact bulk density as well as soil carbon. This means that changes in carbon stocks can be observed just through changes in bulk density to a fixed soil depth. This can improperly suggest progress toward climate mitigation when no true change in carbon sequestration has occurred. To address this, the measurement-based calculation of soil carbon stocks should use equivalent soil mass accounting methods (Wendt and Hauser 2013). Equivalent soil mass accounting methods use mathematical functions to account for the mineral and soil organic matter components of each depth interval to estimate the carbon in a given mass of soil within an area of land (i.e., carbon in a fixed mass of soil as opposed to the carbon in a fixed depth of soil). It should be noted that the field data collected for equivalent soil mass accountings versus bulk density are the same; however, additional depth interval samples for a given depth can help improve estimates.

Table 9.5 Key components of soil carbon stock calculation using direct measurement (cont.)

Key component of soil carbon stock measurement	Discussion
3. Soil carbon measurement	There are several methods for the direct measurement of soil carbon, including elemental analysis (sometimes referred to as dry combustion), loss on ignition, and spectroscopic methods. The direct sampling of soil carbon stock changes to estimate land management CO_2 removals should be based on measuring carbon through combustion in an elemental analyzer.[b] In this method, a soil sample is thoroughly combusted, and the conversion of carbon to CO_2 is measured. Loss on ignition, which measures the mass loss after thermal combustion of a soil sample, should *not* be used, given concerns about its accuracy (Even et al. 2025). More recently, methods such as non-destructive soil spectroscopy have been developed. These newer methods can be advantageous because of their lower per-sample costs; however, the algorithms essential to their implementation require extensive calibration, and concerns remain about the comparability of results generated using different spectroscopy instruments. Currently, there are no consensus methods or training datasets that would ensure comparability of results across laboratories/projects. If soil spectroscopy is used as a measurement approach, samples should be thoroughly dried, ground, and analyzed at a single lab. Mid-infrared instrumentation (as opposed to visual and near-infrared methods) should be used, and the methods and training datasets used to generate estimation algorithms must be thoroughly documented, including the sharing of statistical source code and raw data (Soriano-Disla et al. 2014). Further, at least 20 percent of the samples, randomly chosen, should also be measured using elemental analysis to calibrate any soil spectroscopy protocols. The accuracy of the estimation algorithm should be reported as the root mean square error of carbon content estimated via spectroscopy versus the true carbon content of test samples as measured via elemental analysis. In general, because of among-lab error, soil properties should be measured at a single lab, both within a sampling effort and across sampling efforts (i.e., at different years).

Note: a. Available at SHI SHS Protocol and FAO GSOC-MRV Protocol; b. For example, see the FAO GSOC-MRV Protocol (FAO 2020).

ASSUME NO SOIL CARBON STOCK CHANGE

When land management practices have minimal impacts on soil carbon stocks or annual changes in soil carbon stocks, companies may apply an assumption of no soil carbon stock change. If drained peatlands or other disturbed organic soils are included in the inventory boundary, emissions from those soils must be included (i.e., the assumption of no soil carbon stock change cannot apply). Companies may assume no soil carbon stock change on land under the following land uses and conditions:

- Croplands on mineral soils where there is no conversion of land from other uses to agricultural production, where the land has been under cultivation for at least 20 years, and where no management practice changes that have the potential to impact soil carbon have occurred in the reporting year.
- Pasturelands or grasslands on mineral soils where there is no conversion of land from other uses to agricultural production, where the land has been grazed for at least 20 years, and where no changes have occurred to grazing intensity or other practices that have the potential to impact soil carbon in the reporting year.
- Settlements on mineral soils where there is no conversion of land from other uses, and where no soil excavation or trenching has occurred during the reporting period.
- Other lands on mineral soils where there is no conversion of land from other uses.

Companies assuming no change in soil carbon stocks in the reporting year need to demonstrate that land management activities that have the potential to impact soil carbon are not occurring in the reporting year on relevant lands. If any land management activities may impact DOM carbon, then companies should collect the necessary data to account for the DOM carbon stock change. Examples of such activities include, but are not limited to:

- Management activities on croplands (e.g., changes in crop rotation, tillage intensity, residue treatment, irrigation, or nutrient management) or other physical modification of a field (e.g., tile drain installation, leveling) that have persisted for at least three years prior to the reporting year.
- Management activities on pastureland or grazing land (e.g., significant modification of grazing intensity or other practices) or any physical modification of a field that has persisted for at least three years prior to the reporting year.
- Management activities on ungrazed grasslands that may significantly impact soil carbon stocks, including road construction, site preparation, and prescribed fires.
- Management activities on settlements that may significantly impact soil carbon stocks, including excavation, trenching, changes in land uses within settlements, and changes in landscape management.
- Management activities on other land that may significantly impact soil carbon stocks, including changes in land uses within other lands.

Companies should provide estimates of the soil carbon stock changes as a result of these management changes if they occur on lands owned or controlled by the reporting company in scope 1 or land in the value chain of the reporting company in scope 3. These estimates can be provided using IPCC Tier 1 activity-based methods, using international carbon stock change factors.

9.5.4 Calculating gross biogenic land CO_2 emissions

Reporting gross biogenic land CO_2 emissions is optional and recommended for transparency. Gross biogenic land CO_2 emissions are calculated using flow accounting, based on the gross carbon flow from land-based carbon pools directly to the atmosphere (see Sections 9.4.2 and 3.4.4 for additional background information on flow versus stock change accounting). Gross biogenic land CO_2 emissions are the result of carbon stock losses due to disturbance events such as fires, diseases, windstorms, or other direct CO_2 losses to the atmosphere related to decomposition of DOM and soil organic matter through ecosystem respiration processes. As set forth in Requirement 15, all carbon stock losses on productive agricultural land are considered anthropogenic.

For example, if agricultural residues (e.g., crop residues, orchard trimmings, etc.) are piled up and burned on the land, the resulting CO_2 emissions would be reported as "gross biogenic land CO_2 emissions." Note that "gross biogenic land CO_2 emissions" are distinct from "biogenic product CO_2 emissions" (see Chapter 11), which represent CO_2 emissions that occur at sources where biogenic *products* are combusted or decomposed. In the above example, if such agricultural residues were collected and sold as bioenergy feedstocks (i.e., transferred to the product carbon pool), the emissions resulting from combustion would be reported as biogenic product CO_2 emissions (see Chapter 11).

Biomass carbon stock losses can be represented by two related but distinct parameters: gross biogenic land CO_2 emissions and annual biomass carbon stock losses.

- **Gross biogenic land CO_2 emissions** are expressed in tonnes of CO_2 per year and only include carbon stock losses directly from land-based carbon pools to the atmosphere. Gross biogenic land CO_2 emissions estimates are often based on proxy measurements of gross biomass carbon stock decreases, as opposed to the direct measurement of CO_2 emissions from land-based carbon pools. This approach assumes that above-ground and below-ground biomass entering the DOM and soil carbon pools will eventually decompose and be emitted to the atmosphere. Companies estimate gross biogenic land CO_2 emissions using data on biomass carbon stock losses directly to the atmosphere (e.g., losses through biomass burning) or transfers of biomass carbon to other land-based carbon pools where they will eventually decompose (e.g., losses transferred to dead wood or litter carbon pools). For example, in an oil palm plantation, this would only include biomass carbon losses that are emitted directly from the land (e.g., due to biomass burning) or that remain on the land to decompose from disturbances, pruning, and other residues, but would not include biomass carbon losses associated with harvested fresh fruit bunches.
- **Annual biomass carbon stock losses** are expressed in tonnes C per year and include all carbon stock losses from biomass carbon pools (i.e., including biomass C losses from harvest). This parameter is used in the Gain-Loss equation (see Equation 9.2) to quantify the annual net biomass carbon stock changes. Companies estimate annual biomass carbon stock losses using data on all biomass carbon stock losses, including any harvest, wood removals, fuelwood removals, and disturbances. For example, for an oil palm plantation, this would include all biomass carbon losses due to harvested fresh fruit bunches, biomass burning, disturbances, pruning, and other residues left on the land to decompose.

If companies choose to account for herbaceous carbon stock gains (e.g., in an annual crop system) when applying Equation 9.2, they must also account for herbaceous carbon stock losses. For example, in a typical maize cropping system, only carbon stock gains associated with woody perennial plants (e.g., trees planted as wind breaks) would be included in the estimate of annual biomass carbon stock increases. If companies choose to include any herbaceous biomass gains associated with the maize biomass when applying the Gain-Loss equation, they would also need to account for herbaceous carbon stock losses from harvest, crop residue burning/consumption, or transfers to the DOM or soil carbon pool. See Section 13.5.4 for further discussion.

Where land uses and carbon pools allow for the assumption of no net carbon stock change (see the "Assume no carbon stock change" guidance in Sections 9.5.3.3 and 9.5.3.4), companies do not need to include losses from DOM and soil carbon pools when estimating gross biogenic land CO_2 emissions. Where the assumption of "no net carbon stock change" does not apply, companies must include estimates of net DOM carbon stock losses and net soil carbon stock losses in their calculation of gross biogenic land CO_2 emissions. Gross biogenic land CO_2 emissions can be calculated by multiplying the annual decrease in land carbon stocks that remain in land-based carbon pools on lands included in the relevant spatial boundary by 44/12 (to convert C to CO_2).

Updated tables in Section 5.2.1 in the IPCC *2019 Refinement to the 2006 IPCC Guidelines* provide default values of maximum carbon stock per area and mean biomass carbon loss per area for agroforestry cropping systems (see Tables 5.1 and 5.3 in Chapter 5, Volume 4 in IPCC 2019). Companies should use maximum carbon stock per area values in cases where perennial woody biomass is replaced at or over the year of harvest/maturity under a nominal harvest/maturity cycle, assuming that perennial cropland is harvested and regenerated back into perennial cropland. Carbon losses are estimated by multiplying the annual area of harvested or replaced cropland by the maximum carbon stock per area factor. Statistical databases (e.g., FAOSTAT) and other sources can be used to estimate the area of land under perennial woody crops, and area estimates can be further subdivided into general climate regions or soil types to match default biomass loss values.

Equation 9.3 is used to estimate the annual carbon stock loss due to disturbance, one component of both gross biogenic land CO_2 emissions and annual biomass carbon losses. To estimate gross biogenic land CO_2 emissions from fires, companies may also apply Equation 10.19, using IPCC emission factors for CO_2. To estimate gross biogenic land CO_2 emissions or annual biomass carbon losses from disturbances other than fire (e.g., mortality due to pests, disease, windstorms, etc.), IPCC guidelines for national GHG inventories provide global Tier 1 emission factors to estimate annual carbon losses due to disturbance based on average biomass for specific vegetation types by land use. Companies may assume all biomass is lost in the year the disturbance occurs, unless they know the fraction of biomass lost in the disturbance.

Companies may obtain Tier 2 data on gross land carbon stock losses from the published peer-reviewed literature or may use data from relevant national GHG inventories to estimate gross biogenic land CO_2 emissions. Where Tier 3 methods are applied, companies may sample gross land carbon stock losses due to fire, disturbances, or soil respiration from repeated measurements in sample plots in accordance with measurement-based approaches or model land-based CO_2 emissions based on calibrated model-based approaches.

Equation 9.3 Annual biomass carbon stock losses from disturbances

$$L\_D = \sum_{d} (A\_D_d \times B_d \times (1 + R) \times CF \times f\_D_d)$$

Description		Unit	Source
L_D	Carbon stock loss (*L*) due to disturbance (*D*)	tonnes C (year)$^{-1}$	Calculated
A_D_d	Area that is affected by disturbances by disturbance type *d*	ha (year)$^{-1}$	User input
B_d	Average above-ground biomass of land area affected by disturbances by disturbance type *d*	tonnes dry matter (ha)$^{-1}$	User input
R	Ratio of below-ground biomass to above-ground biomass	tonnes dry matter below-ground biomass (tonnes dry matter above-ground biomass)$^{-1}$	User input
CF	Carbon fraction of dry matter	tonnes C (tonnes dry matter)$^{-1}$	User input
f_D_d	Fraction of biomass lost in disturbance, by disturbance type *d*	dimensionless	User input
d	Disturbance type		

Source: Adapted from Equation 2.14 in IPCC (2006), Volume 4: Section 2.3 ("Generic methodologies applicable to multiple land-use categories"). Note that accounting for gross biogenic land CO_2 emissions on forest lands is not covered in version 1 of this *Standard.*

Endnotes

1 This text includes elements that may change to align with the resolution on forest carbon accounting in future versions of this *Standard*. See Box 9.1.

2 Where no uncertainty ranges are provided by IPCC national inventory guidance, companies may apply an uncertainty range of ±90 percent of the estimate provided. IPCC 2006, Volume 4, Chapter 2.

3 For example, see sampling designs for national forest inventories in McRoberts et al. (2015).

4 For example, see resources and guidance available for terrestrial plants at the National Ecological Observatory Network (NEON) facility funded by the United States National Science Foundation, available at https://www.neonscience.org/data-collection/terrestrial-plants.

5 For further guidance on Tier 1 and Tier 2 approaches, see Section 2.3.3 in Chapter 2 and Section 5.2.3 in Chapter 5 in IPCC (2019a).

6 IPCC 2014.

7 For further guidance on Tier 2 approaches, see Section 2.3.3 in Chapter 2 and Section 5.2.3 in Chapter 5 in IPCC (2019a).

8 Available at https://unfccc.int/ghg-inventories-annex-i-parties/2020.

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