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C-sequ
Life cycle assessment guidelines for calculating carbon sequestration in cattle production systems

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ABSTRACT

The concept of carbon sequestration is acknowledged as a potential way for agriculture to not just emit carbon dioxide, but store it, removing it from the atmosphere. Up until now there has been no consensus on an appropriate LCA-based approach for application in cattle production systems to quantify carbon removals. The focus has always been on emissions only. As the cattle sector works towards net zero ambitions, an appropriate science-based approach is required to not only account for emissions but also quantity carbon removal as part of the GHG footprint reporting.

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GLOSSARY

Carbon dioxide removal: The process of capturing carbon from gaseous CO_2 from the atmosphere and keeping it from re-emission through storage in organic or inorganic carbon.

Carbon sequestration: The process where CO_2 is removed from that atmosphere and stored in organic stocks (e.g., soil, trees).

Carbon sink: Any process, activity or mechanism which removes CO_2 from the atmosphere.

Carbon stock: The quantity of carbon in a carbon pool i.e. a reservoir in an earth system.

Carbon stock emission: Carbon stock emissions are losses of stock below the reference state and do not include carbon emission from the breakdown of carbon added to soils e.g. through composts or residues.

Characterization factor: Is a factor that is applied to convert an inventory flow to an impact category indicator, such as CO_2eq in the case of climate change.

Climate benefit: For the purpose of the Guidance the phrase “climate benefit” refers to a removal of CO_2 from the atmosphere which is accounted as a negative emission of CO_2, while acknowledging that negative emissions associated with any given system is not equal to a global climate benefit.

Climate impact: For the purpose of the Guidance the phrase “climate impact” refers to an emission of CO_2, while acknowledging that emissions for any given system is not equal to a global climate impact.

Discrete event: Discrete events are land use changes, land management changes, floods, fires and other events that induce a change in carbon stock.

Inventory: Inventory is the accounting of flows that describe the inputs/outputs of a system, such as the emission of CO_2 from a hectare of land.

Land management change (LMC): A change in land management that occurs within a land use category.

Land use: The total of arrangements, activities and inputs applied to a parcel of land. The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction). Land use is classified according to the IPCC land use categories of forest land, cropland (annual and perennial), grassland, wetlands, settlements, other lands.

Land use change (LUC): The change from one land use category to another.

Neutralization: The “cancelling out” of a CO_2 emission by removing carbon from the atmosphere (for a sufficient amount of time).

Responsibility window: The period of time a product system is responsible to carry the impacts or benefits of gains and losses of sequestered carbon. The responsibility window determines the reference state and the total relevant inventory for an assessment year.

Reference state: The reference state is the carbon stock quantity in units of stoichiometric CO_2 per land area to which cumulative changes in net carbon stock are considered. The reference state is defined as the stock amount just prior to the initiation of the responsibility window.

Stoichiometric CO_2: Carbon stocks within soils or biomass that are calculated in units CO_2 by adjusting by the molecular weight ratio of CO_2 to carbon 44:12.

Stored CO_2: In this guidance, stored CO_2 refers to keeping sequestered carbon out of the atmosphere and in a carbon stock.

1 INTRODUCTION

They say, *if it were easy, it would have been done by now*…..Well that is certainly the case with carbon sequestration, translating the science into robust practical application with targeted outcomes at the farm level.

This project which started in 2018, is a genuine effort from partnering organizations from the dairy and beef cattle sectors to assimilate the scientific underpinning of this complex subject and build a methodology to quantify the sequestration from cattle production systems in different geographies. Carbon sequestration is often quoted as being a major tool in the GHG mitigation toolbox. For the concept to be applied and generate the desired impact – science-based application and quantification is a fundamental step forward. The partners in this project appreciate that sequestration will not solve the climate crisis on its own, though do recognise that in agriculture it has the potential in many instances to make a substantial contribution.

The C-Sequ project has been a transparent process involving a considerable number of global academics, specialists and industry stakeholders providing invaluable insights through a series of meetings, webinars and document reviews on how to translate this challenging and complex topic into a practical and science-based farm scale application. In addition, the C-Sequ approach has considered the work of others in this space and has aligned where appropriate and possible with these developments. Indeed, the C-Sequ process benefited directly from the input provided by these initiatives for which the Partners are grateful. The C-Sequ Partners are also appreciative of the expertise and guidance delivered by Quantis in providing the technical development aspects of this project, ensuring that the methodology was aligned with the latest science, guidance and best practice.

Initially the partners' ambition was to develop a 'bolton' module for existing LCA methodologies in particular, the International Dairy Federation's Common Carbon Footprint Approach for the Dairy Sector. Through the development phase it became apparent that due to limited data availability and levels of uncertainty, to have the 'one number' remains a challenge from a transparency perspective. The recommendation in this version of the methodology and in alignment with ISO 14067, remains to report sequestration separately to the carbon footprint results generated through the Life Cycle Assessment process.

The project partners recognize that there is considerably more to do and this first approach in standardizing an implementable process is merely an important first step in the right direction for the cattle sector (in fact all agriculture). Importantly, C-Sequ is designed to encourage the implementation of positive (additional) farm management practices that both promote and retain carbon in the soil and vegetation in a quantified way.

This document is the culmination of several year's work invested by a number of stakeholders who kindly supported the C-Sequ partners with their ambitions.

The guidelines include changes based on the public consultation period that took place November 2 – December 9, 2020. The consultation also captured feedback to decipher appropriate approaches for inclusion. For example, the required 20-year responsibility window is a result of the unanimous response received through the consultation process.

In addition to the public consultation phase, this methodology also benefits from the undertaking of 50 farm-level pilots implemented by the project partners across a number of geographies and a range of dairy production systems. The pilot process provided invaluable insights – It is all very well having a methodology – applying that methodology is another learning experience all-together! This methodology is certainly a more robust outcome as a result of investing in the pilot process.

Considering the fast-moving pace of science and accepted practice in the topic of sequestration, this guideline will be regularly reviewed and updated to ensure it remains at the cutting edge and that the cattle sectors can be confident that the quantification of efforts is delivered in a robust and responsible way.

2 MOTIVATION FOR THE GUIDELINES

When coupled with greenhouse gas emission reduction strategies, long-term CO_2 removal increases the likelihood of achieving 1.5 degree Celsius climate targets (Canadell and Schulze 2014; Rogelj et al. 2018). Furthermore, there is consensus that reducing the release of stored carbon in peatlands and other land types, is an essential mitigation pathway to limit warming to 1.5°C above pre-industrial levels (Rogelj et al. 2018).

Figure 1. is a schematic of the carbon cycle of a grazed pasture. Soil organic carbon (SOC) is composed of several carbon pools: recently dead organic matter (from plant residues), as well as particulate organic carbon from previous decomposition, and humus and recalcitrant organic carbon. Carbon pools have different chemical compositions and removal/replacement rates (i.e., turnover). Land management and natural conditions can influence the composition of carbon pools in any agricultural system and their turnover influenced by erosion, microbial respiration, migration to the subsoil, and introduction of organic matter and nutrients to the system. Carbon pools in pastures and most agricultural systems are comprised of plant residues (i.e., shoot and roots residues) and particulate organic carbon (i.e., pieces of plant debris 0.053-2 mm in size) which are "labile carbon" with relatively fast turnover. Labile carbon is more affected by land management practices on a relevant timescale (Bell and Lawrence 2009). This guidance focuses on methods to account for changes in carbon stock due to influence of management on labile carbon.

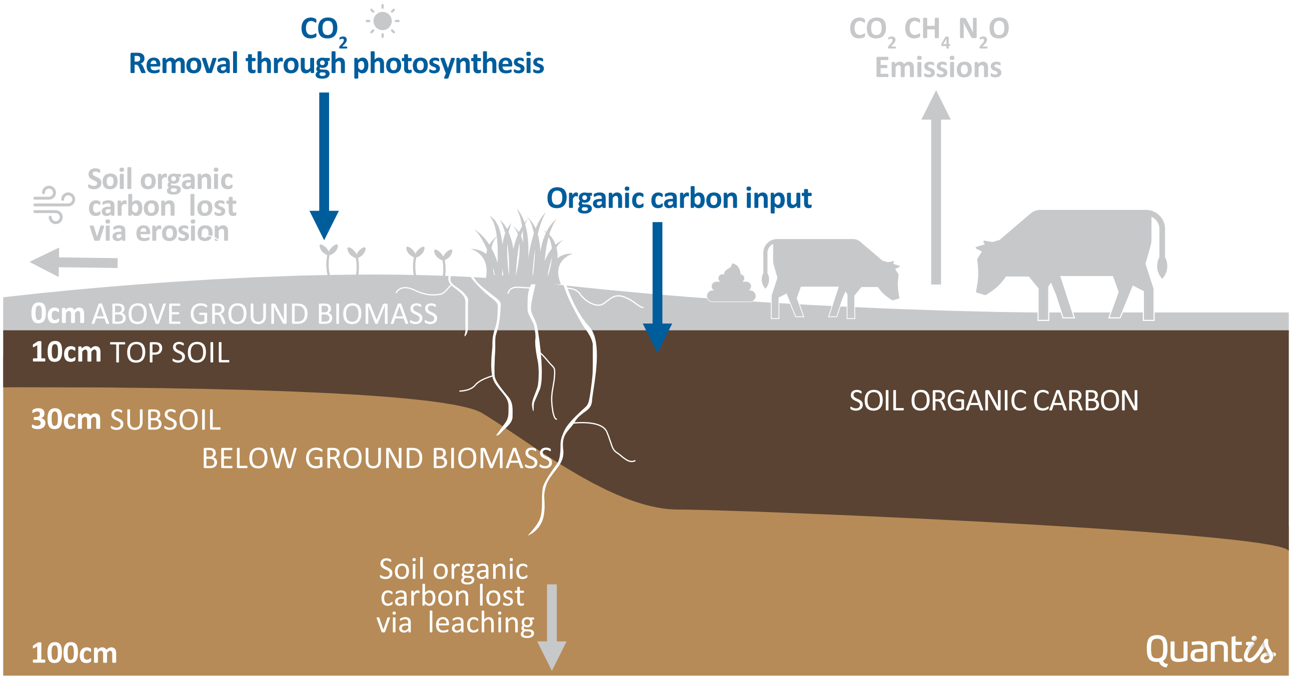

Figure 1. Fundamentals for inventory: Carbon cycle

Inspired by greenhouse gas (GHG) accounting challenges in the forestry and bioenergy sectors, there are many peer-reviewed methods that aim to quantify the climate impact of reversible CO_2 removal from the atmosphere (Levasseur et al. 2011; Brandão et al. 2018; Cherubini, Guest, and Strømman 2013; Guest et al. 2013; Breton et al. 2018; Bessou et al. 2019). These methods provide different frameworks to quantify the impacts and benefits of CO_2 flows in and out of the atmosphere over a period of time. The climate benefit of either delaying an emission of CO_2 or temporarily removing CO_2 from the atmosphere are considered the same in most methods (Levasseur and Brandão 2012). (Throughout this document the term "impact" refers to a climate relevant emission of CO_2 and the term "benefit" refers to the removal of CO_2 from the atmosphere through carbon sequestration which is accounted for as a negative emission.) All reviewed methods showed a climate benefit for removing CO_2 from the atmosphere for longer periods of time and delaying its potential re-emission.

Common to all these methods is that the climate impact of carbon flows is mathematically tied to

1. **the amount of CO_2 added to or removed from the atmosphere.**
2. **the change in radiative forcing—over a given time period—in relation to a reference pulse emission of CO_2.**

In LCA terminology these two aspects are referred to as 1) inventory flows and 2) impact characterization. A commonly used CO_2 characterization framework is standardized by the Intergovernmental Panel on Climate Change (IPCC) e.g. the 5th Assessment Report published in 2013.[1]

1 https://www.ipcc.ch/report/ar5/wg1/

The fundamental framework of CO_2eq characterization implies that climate change due to radiative forcing is a function of the relative GHG concentration, including CO_2, in the atmosphere over time. To standardize GHG accounting, the metric “CO_2-equivalent (CO_2eq)" was developed, meaning that the impact of all GHGs is considered in reference to the impact of CO_2. The foundation of the CO_2eq factor for any GHG (e.g., N_2O, CH_4) is the measure of its climate impact relative to the climate impact over a fixed time horizon following a pulse emission of CO_2. The ratio of this relative impact is the characterization factor in units of CO_2eq. Conventionally, the time horizon for CO_2eq characterization is 100 years to protect human life on earth today and the next generation. This is referred to as global warming potential (GWP100) and a set of commonly used characterization factors are available in the IPCC, 2021 AR6 (IPCC 2021). This characterization framework is essential to consider when accounting for carbon sequestration in terms of CO_2eq.

In practice the application of CO_2eq accounting implies that, 1 t CO_2 stored as organic carbon in biomass or soil stock in one year, is not the same as -1 t CO_2eq emission neutralization unless there is the assurance it will be stored in the long term (e.g., >100 years). Thus an inventory of 1 t CO_2 stored only in an assessment year cannot “cancel” the emission of 1 t CO_2eq of fossil CO_2 in the assessment year which influences atmospheric concentration for 100 years. Furthermore, removal of CO_2 from the atmosphere through carbon sequestration is not the same concept as reducing an emission or footprint which implies a reduction of an emission source.

Given the scientific evidence that longstanding CO_2 removal can help achieve climate targets, there is interest in the potential to store CO_2 in agricultural systems through carbon sequestration. Carbon sequestration is defined in this document as CO_2 that has been removed from the atmosphere and stored in organic stocks (e.g., soil, trees). There is also interest in changing agricultural practices to avoid or reduce the emission of (previously) sequestered carbon in land areas such as peatlands where agriculture takes place. Given the recent activity and attention surrounding this topic, there is a need for standard guidance on how to account for gains and losses of sequestered carbon in dairy and beef (or other agricultural) LCAs, carbon footprinting, and GHG accounting. Without guidance, carbon sequestration is not usually included in current LCA practice, and there are inconsistencies across assessments and approaches.

One common inconsistency is that inventoried “stoichiometric CO_2” (carbon stored in trees and soils multiplied by the molecular weight ratio of 44/12) is incorrectly considered equal to characterized “CO_2eq.” Stoichiometric CO_2 reported at the inventory level is common in national inventory accounting, carbon credit markets and other accounting frameworks. Although reporting stoichiometric CO_2 is appropriate to report inventory, in many assessments (both in the public and private sphere), stoichiometric CO_2 is erroneously subtracted from or used to offset emissions in terms of CO_2eq. This mixes metrics in an inappropriate way. Accounting for stoichiometric CO_2 without adjusting to the metric CO_2eq overestimates the benefits of carbon sequestration when it is not permanent and if permanent this approach concentrates the climate benefit over the next 100 years into 1 year. One argument for this type of accounting is that it represents “real-time” flows in a given year – however this logic is not aligned with CO_2eq metric that represents 100 years of influence on the atmosphere.

Assumptions of permanency and how this is treated are another inconsistency across current assessment frameworks. If carbon sequestered in an agricultural system is assumed to be permanent and the full climate benefit to be seen over the next 100 years due to removal of CO_2 is then attributed to an assessment year, that year is obtaining credit for future climate benefits that may not occur. If sequestration is assumed permanent or longstanding, like biochar application (Lehman et al. 2015, Paustian et al. 2019), there remains a question of which year the full climate benefit (over the 100 year period of GWP100) should be credited to, for example if it should be concentrated into one year or distributed over several years. Permanent or long-standing carbon sequestration is the ultimate goal to achieve climate targets. Even with the intention of continued practice, carbon sequestered in agricultural systems can be reversed and the CO_2 re-emitted to the atmosphere due to changes in land management, land use or other events (e.g., fires, floods, frosts etc.).

As conceptually illustrated in Figure 2, several studies and models (Coleman and Jenkinson 1996, Peterson et al. 2013, Horrillo et al. 2020) demonstrate that a large proportion of carbon applied to a soil in a given year (e.g., through compost, manure, residues) will return back to the atmosphere over the next 100 years. After application of carbon to the soil, its emission depends on geospatial conditions (e.g., soil type, temperature and moisture) and practices (e.g., tillage). Thus organic carbon needs to be continuously added to the soil to build carbon stock (i.e., the stored carbon) over time and to sustain the built stock. (The carbon that returns to the atmosphere from application of compost, manures and residues is usually not climate relevant as it is part of the fast-cycling carbon cycle; however if the composts are made of peat soil or some other ancient form of carbon, the emission could be climate relevant.)

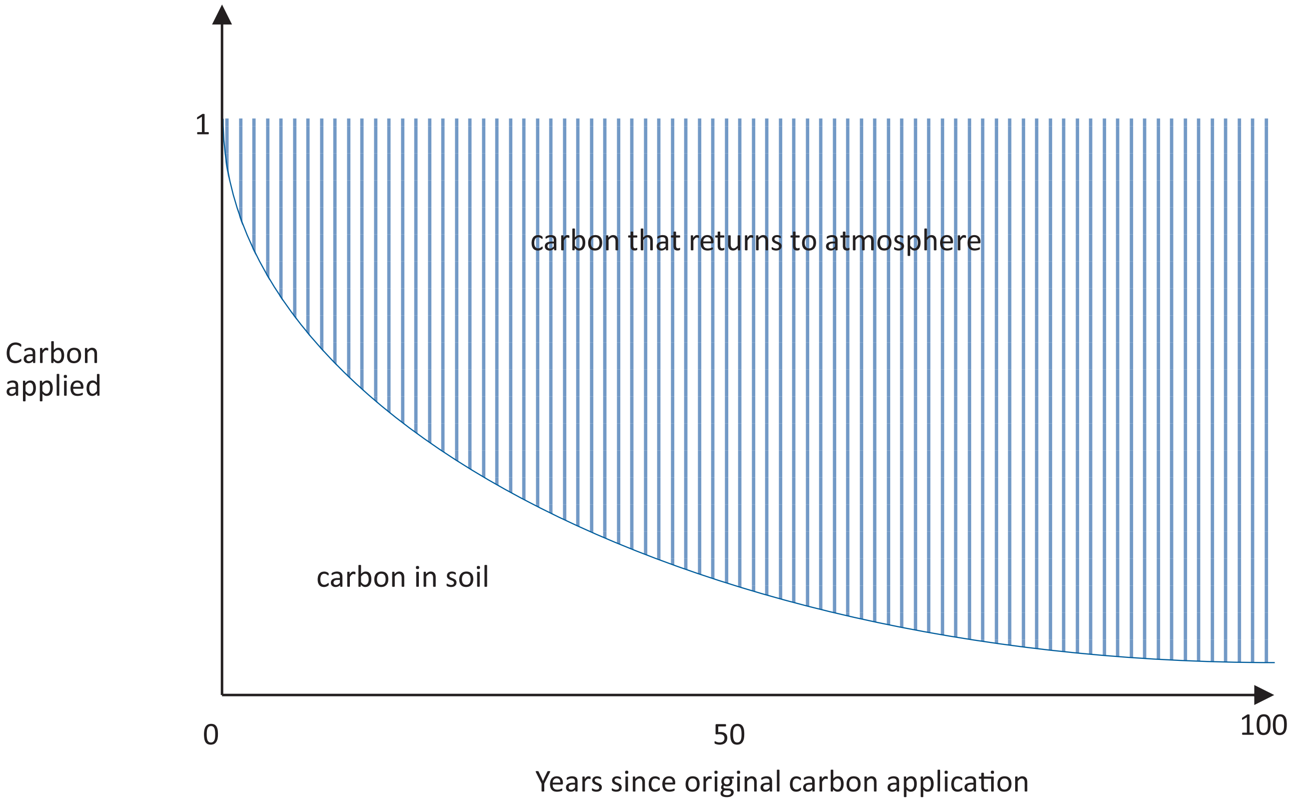

Figure 2. Conceptual illustration of the evolution of the fate of a pulse addition of carbon to the soil; this is the fraction of carbon remaining in the soil over time after an addition of carbon to the soil at time zero (adapted from Petersen et al 2013).

Another example of inconsistent accounting is with respect to releases of sequestered carbon through land management. Current Guidance for land use change (LUC)[2,3], include CO_2 emissions from losses of carbon stock in soils or trees due to agricultural activities. Changes in land management practices that do not qualify as a land use change, may also influence loss (or gain) of carbon stock; however, changes in carbon stock due to land management are not typically considered as climate relevant in current LCA practice. Excluding these emissions is problematic as there is growing evidence that changing land management to limit emissions of CO_2, e.g. from rewetting drained peatland through flooding, is key to reach global climate targets (Ekardt et al. 2020; Günther et al. 2020; Leifeld and Menichetti 2018).

Yet another inconsistency in the accounting of carbon sequestration is the time period over which the entity shall take responsibility for losses or gains of sequestered carbon. As an example, in practice LUC accounting includes amortization of impacts often over a 20-year responsibility time period (e.g., each year following an event gets 1/20th of the total impact). There is no existing Guidance for an amortization window or responsibility timeframe for carbon sequestration accounting, which can lead to inconsistencies across assessments.

2 https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf
3 https://quantis-intl.com/strategy/collaborative-initiatives/accounting-for-natural-climate-solutions/

Finally, as another inconsistency there is an ongoing debate about the choice of reference state (historical state, potential state, average or maximum) in accounting frameworks involving land (for both carbon and biodiversity). The guidance recommends a historical reference state to align with existing guidance for accounting land use and management change (WRI 2011). Depending on the goal and scope of an LCA a different reference state may be desired (Hauschild and Huijbregts 2015).[4]

These examples of inconsistent and, at times, incorrect GHG accounting pose a risk to identifying appropriate and practical strategies towards global climate goals related to increasing and keeping carbon sequestered in land-based systems. Thereby a standardised Guidance for carbon sequestration accounting is needed to clarify the collection of inventory, the characterization as CO_2eq, the identification of events beyond LUC that can influence carbon stocks, and the timeframe over which responsibility is taken. The conceptual approach in this Guidance builds on previous work for carbon market policy often referred to as the “tonne year” approach (Murray and Kasibhatia 2013), and dynamic accounting approaches described by peer reviewed articles (Levasseur et al. 2011; Brandão et al. 2018; Cherubini, Guest, and Strømman 2013; Guest et al. 2013; Breton et al. 2018; Bessou et al. 2019). The Guidance provides methods that are suitable for annual accounting of farm-level impacts, and a practitioner can use the concept to perform various types of LCA (consequential, attributional, prospective etc.) depending on the research or decision-making question. The rules for including carbon sequestration in GHG Protocol reporting e.g. for Science Based Targets as well as ISO compliant LCAs are (at the time of the creation of this Guidance) under development.

4 See chapter 11 “Land use” by Milà I Canals & de Baan

3 CONCEPTUAL OVERVIEW

The Guidance presents a framework for how to consider the impacts and benefits of losses and gains of carbon sequestration within a farm-level LCA.

It does this by focusing on land management change within a land use category, and complements (but does not replace) land use change accounting.

The following concepts are detailed in the document:

- the responsibility window and reference state.
- the key inventory flows:
  1) CO_2 stored which describes the CO_2 removed from the atmosphere through carbon sequestration and represents building carbon stock above a reference state. An example is carbon stock gain through tree or hedge planting.
  2) CO_2 stock emitted which describes CO_2 emitted to the atmosphere due to losses of carbon stock below a reference state. This inventory flow is analogous to biogenic CO_2 release through land use change. Inventory can be an average yearly value over a time period.
- land management change, continuous practices, and various inventory collection methods.
- the characterization factors that multiply the key inventory flows to arrive at the climate-relevant metric CO_2eq as aligned with GWP100 accounting

As for the calculation of inventory flows, because measures and estimates of carbon stock change is an area of ongoing research and can be site-specific, the guidance does not require a single model or approach to estimate or measure stock change, but recommends using higher tier models when possible (see Section 5.5). If a process-based model is used, a recommendation is to use it to estimate the stock change for the year(s) being assessed.

A key concept in the accounting of inventory is the climate relevance e.g. over a GWP100 accounting timeframe. Land management changes that lead to carbon sequestration should be intended to be longstanding in order to have maximum climate benefit. Carbon sequestration through soils and biomass is, however, reversible given a future change in land management, land use or some other event (fire, flood). **Given reversibility, the Guidance follows the precautionary principle that any sequestered carbon through land-based solutions may be reversed, after which there is no longer a climate benefit.** This accounting approach removes the need to consider the future and allows for a continuous accounting of the benefit of keeping CO_2 stored through continuing practice.

The characterization factor proposed to align with GWP100 and the Bern Carbon Cycle IPCC model, is -0.01 kg CO_2eq/kg CO_2-year stored following suggestions by the International Reference Life Cycle Data (ILCD) documentation by the European Commission (JRC-IES 2010) and reviews by other authors (Brandão et al. 2019; Levasseur and Brandão 2012). The interpretation of this characterization factor is that 100% of the neutralization benefit of an increase in carbon stock can only be achieved after 100 years of storage.

Ensuring a given land management practice for 100 years is not a relevant timeframe for most management decisions and contracts. Therefore, there are two main value choices presented in this Guidance to complement the ILCD approach, one where permanency cannot be ensured and one where permanency can be ensured. The conditions under which permanence can be ensured are not presented in this Guidance and are likely to be presented in other protocols such as the GHG Protocol, or European Commission rules. For example, the European Commission Carbon Farming report section 5.6 outlines various ways of ensuring permanency in different emission schemes (COWI 2021).

If permanency cannot be ensured, the benefits of a full neutralization are spread over a relevant management period. The value choice of having an accountability timeframe is referred to in this document as a responsibility window, and the characterization factor of -0.01 kg CO_2eq/kg CO_2-year stored must be adjusted to fit the responsibility window. As a value choice to encourage agricultural practice change on a manageable timescale, the public consultation process of this document suggested a responsibility window of 20 years. The interpretation of this value choice is that each year for 20 years following an annual gain in carbon stock a credit of -0.05 kg CO_2eq/kg CO_2-year stored can be received if the carbon stock remains. This implies that sequestered carbon receives 100% of its neutralization benefit for over a 20-year period (5% each year it remains stored). After a 20-year period, the credit expires and if the stored carbon is released, then it is treated under the same rules as land use change (LUC) accounting. This Guidance does not provide recommendations for how to account for avoided emissions e.g., conservation or keeping carbon stored that has been previously stored (e.g., longer than 20 years ago). Release of previously stored carbon, however, would result in a climate relevant emission.

If permanency can be ensured (e.g., through contract), then a time-sensitive characterization factor is not required, and the full neutralization benefit of the inventory can be taken in the year in which the stock gain occurs (this basically would mean skipping the entire inventory characterization Section 6 of the Guidance). If the stock is lost in future years, it is then recommended to treat the emission analogous to LUC.

Ensuring permanence

Assuming permanency without an amortization period for a benefit or not using characterization to account for climate impact in a GWP100 framework, is typical of various types of carbon crediting and non-LCA related carbon assessments. Carbon crediting markets may apply a risk, buffer, or safety factor to account for impermanence e.g. due to natural events such as forest fires, floods or require certain verification or monitoring. In the case of assuming permanency in LCA for reporting or making claims for products or corporate footprints, there are several key unanswered questions such as: What needs to be true to ensure a management change or sequestered carbon is permanent? What monitoring rules would be required? Would there be a penalty for changes that are not permanent e.g. through characterization of biogenic CO_2 releases as 1 kg CO_2eq/1 kg CO_2 biogenic emitted? Answering these questions is not a focus in this version of the Guidance.

The conceptual framework provided allows practitioners to account for gains and losses of carbon sequestration for farm-level accounting. For this reason, and given yields are variable, the Guidance provides a framework for accounting inventory per hectare of land. When going from hectare to kilogram of product (i.e., to express as an 'emission intensity') practitioners can follow existing methods (e.g., the impact per hectare divided by the yield). Allocation factors may need to be applied according to already existing LCA guidance and common practice. As an example, when applying the Product Environmental Footprint (PEF) method of the European Commission and the circular footprint formula (CFF), it could be interpreted that the benefits of carbon sequestration related to applying composts should be allocated to both the compost system and the farm system. This type of allocation can encourage equally the production of compost and application of compost.

In summary, this document is a first step to provide practical guidance to account for gains and losses of sequestered carbon specifically to support farm-level management changes with a focus on the dairy and beef sector. The quantitative framework is built on existing peer-reviewed work and aims to encourage land management that A) removes more CO_2 from the atmosphere for longer periods of time and B) keeps carbon stocked in land and biomass from being emitted.

The Guidance offers recommendations for practitioners (trained professionals who perform LCA or GHG accounting) to include carbon sequestration in a way compatible with the current state of academic knowledge and practice in LCA and other GHG accounting frameworks.

To bridge the gap between academic knowledge and practice, the Guidance recommends pragmatic and robust simplifications to limit the number of manual operations to be carried out by the practitioner. As with all GHG accounting there is a subjective nature to the decided rules and thereby this document aims to transparently provide proposals for guidance on how to account for gains and losses of sequestered carbon in farm-level LCAs.

Any comparative claims made public shall be ISO compliant with standard 14040. Given this is an evolving topic within GHG accounting, results calculated using the conceptual framework in the Guidance shall be reported separately with respect to the total carbon footprint especially when used for public communication.

4 GUIDANCE AT A GLANCE

The Guidance provides recommendations for when and how to account for farm-level losses and gains of carbon sequestration in practical LCA and GHG assessments. In summary, the approach is outlined by the following framework (Figure 3):

4.1. CONSIDER A RESPONSIBILITY WINDOW AND SELECT REFERENCE STATE

The responsibility window is the number of years over which impacts or benefits due to an action in a given year are carried. For practical reasons, the Guidance suggests that the number of years for which a practitioner can “look back” in the past to consider discrete events is the same amount of time as the responsibility window. Discrete events are land use changes, land management changes, floods, fires, and other events that change carbon stock. Discrete events include both intentional and unintentional changes in carbon stock as the effect of an emission or removal on climate is not considered in relation to its intention. Other protocols or guidance documents may require differentiating intentionality. The reference state for an assessment is recommended to be the stock (soil and biomass) just prior to the first discrete event in a responsibility window or in the absence of a discrete event (i.e. for continuous practice), at the beginning of the responsibility window. Piloting of the draft guidance demonstrated that identifying a discrete event can be challenging when management practices have been in place for an extended period of time and there is evidence of carbon stock gain. In this case, please see the continuous practice section 5.4. The climate benefits or impacts due to relevant changes in carbon stocks (changes from reference state) shall be carried forward for the duration of a responsibility window. A responsibility window of 20 years was selected through a public consultation process. The responsibility window will ultimately also adjust the characterization factor. Only one responsibility window shall be provided in the Guidance, but various responsibility windows or look back period can be appropriate for specific decision-making scenarios.

4.2. COLLECT INVENTORY

The Guidance focuses on two main inventory flows: 1) CO_2 stored, 2) CO_2 stock emitted. Climate relevant inventory shall capture net gains and/or losses of carbon stock in soils and biomass in the units of stoichiometric CO_2 per land area relative to a reference state.

4.3. CHARACTERIZE INVENTORY

The characterization factor for potentially reversible carbon stock gains above the reference state is suggested as -0.01 CO_2eq/CO_2 stored-year applied over 100 years, which is aligned with GWP100. The characterization factor for carbon stock emissions i.e., loss of stock below the reference state, is suggested to be 1 CO_2eq/CO_2 stock emitted applied in a single year. The asymmetry in these values physical represents that most carbon sequestration can be reversed, where as an emission cannot be reversed. Nevertheless, considering a responsibility window of 20 years, leads to symmetrical final adjusted characterization factors. The guidance recommends equal distribution of impact and benefit over a 20-year responsibility window, which results in final adjusted characterization factors of -0.05 CO_2eq/CO_2 stored-year in the case of a stock gain and 0.05 CO_2eq/CO_2 emitted-year in the case of a loss of stock. In both cases the benefit and impact shall be carried for 20 years.

1. Responsibility window & reference state

Identify the responsibility window (which is proposed to be 20 years) and identify the reference state, i.e. what changes has taken place during the last 20 years (=RW).

2. LCI

Defining total removals and emissions for the assessment year.

- Empirical soil organic carbon (SOC) models (e.g., IPCC Tier I and Tier II models)
- Process-based SOC models (e.g., RothC, Century SOC Tier III models)
- Measurements (e.g., soil organic carbon samples)
- Allometric equations for perennial biomass trees and hedges, (e.g., IPCC Tier I methods, and academic literature), and related input variables needed (e.g., diameter at breast height and height)

3. Characterization

How to account removals and emissions in carbon dioxide equivalents (CO_2eq):

- Adjusted characterization for reversible removals (carbon stored): -0.05 CO_2eq/CO_2 stored-year
- Permanent removals (carbon stored): -1 CO_2eq/CO_2 stored permanently (with optional amortization, e.g. over 20 years)
- Adjusted characterization for emission of carbon stock: 0.05 CO_2eq/CO_2 emitted-year (as aligned with land use change accounting with 20 year amortization - otherwise 1 CO_2eq/CO_2 emitted-year)

Figure 3. Outline of the steps to quantify carbon removals and emissions

More details on the practical implementation of these steps are provided in the following sections.

5 RESPONSIBILITY WINDOW AND REFERENCE STATE

In existing land-based carbon accounting there is consideration of an amortization period which is often set to 20 years. The amortization period is the period over which the responsibility for impacts is carried and distributed.

In Land Use Change (LUC) accounting as outlined by the GHG Protocol Agricultural Guidance[5], the reference state (i.e., prior land use) can be set with respect to the "look back" or assessment period which is equal to the amortization period. In this Guidance we refer to the period of time to "look back" and the amortization period, which are recommended to be equal, as the "responsibility window" which is the period of time a system "carries responsibility" for climate impacts or benefits related to gains or losses of sequestered carbon with respect to a reference state.

The responsibility window shall be initiated by a discrete event. As aligned with *The Land Use, Land-Use Change, and Forestry Guidance for GHG Project Accounting Protocol*[6], **a discrete event is when there is a land management or land use change or some other event (e.g., fire) that disrupts carbon stock** within the responsibility window (e.g., past 20 years). In absence of a discrete event the responsibility window can be initiated as the assessment year minus the duration (number of years) of the responsibility window (Section 6.4). Although the responsibility window of 20 years is suggested, the responsibility window is sensitive to case-by-case decision making especially in the case of perennial or native vegetation regeneration (e.g., the responsibility window should be relevant for the perennial cycling).

Practitioners are encouraged to investigate the "look back" period through questionnaires with farm managers, satellite imagery, or other legal or certifying documents that qualify land use and management. As an example, when the responsibility window is 20 years, a practitioner shall look back over 20 years (e.g., using satellite imagery or land tenure information) to determine the presence of a discrete event.

There are several implications for the responsibility window on the collection of inventory and the final distribution of results over the time period, which can be pragmatically

5 https://ghgprotocol.org/agriculture-
6 https://ghgprotocol.org/sites/default/files/standards_supporting/LULUCF%20Guidance_1.pdf

calculated through an adjusted characterization factor. The responsibility window marks the time period for which the practitioner can take responsibility for losses or gains of carbon sequestered that have happened in the past. In the case of stored carbon, the inventory from previous years (i.e., a land management change initiated 5 years ago that has stored carbon each year) can be considered in a given assessment year only if the previously sequestered carbon remains stored in the system by the action in the assessment year. Another implication of the responsibility window is that the entire benefit or impact shall be distributed over the responsibility window. For example, within the GWP100 framework, the benefit of gains of carbon sequestration the characterization factor (CF) of -0.01 kg CO_2eq/kg CO_2 stored-year, requires 100 years to obtain the full climate benefit. The equation for the final adjusted characterization factor is as follows:

$$CF_{adjusted} = \frac{CF_{time\_horizon\,=\,100}}{RW} = CF_{annual} = \frac{100}{RW} \qquad \textit{Equation 1}$$

Where $CF_{time\_horizon=100}$ refers to considering 100 years to obtain the full benefit or impact considering GWP_{100} scenario, and the responsibility window (RW) is recommended as 20 years. As an example, the annual CF, or CF_{annual} = -0.01 kg CO_2eq/kg CO_2 stored-year over 100 years ultimately yields the full benefit of $CF_{time\_horizon=100}$ = -1 kg CO_2eq/kg CO_2 stored. When RW = 20, this results in a 5% per year or -0.05 kg CO_2eq/kg CO_2 stored-year as an adjusted characterization factor. As another example 1 kg CO_2eq/kg CO_2 emitted-year is already accounting for impact over a 100-year time horizon as emissions are not reversable. When RW = 20, this results in is 5% per year or 0.05 kg CO_2eq/kg CO_2 emitted-year as an adjusted characterization factor.

Given subjectivity of choosing a responsibility window, public consultation was invited to work towards consensus towards a final choice of responsibility window. Responsibility windows of 20, 50, and 100 years were proposed. Resulting from the public consultation a 20 year responsibility window was chosen.

The advantages and disadvantages of proposed responsibility windows are described in the appendix Table A1. Responsibility windows that were submitted for public consultation. Responsibility windows that were submitted for public consultation; public scrutiny of these factors was invited from November 2, 2020 to December 9, 2020. The current recommendation is that the responsibility window would be the same for gain or losses of sequestered CO_2.

6 INVENTORY COLLECTION

Life cycle inventory (LCI) is a key part of the LCA framework.

There are two main inventory flows introduced in the Guidance that are climate relevant:

1) CO_2 stored which describes the CO_2 removed fromthe atmosphere through carbon sequestration and represents building carbon stock above a reference state. Examples could be carbon stock gain as biomass through additional tree or hedge planting, or carbon stock gain as soil organic carbon through a change to high organic carbon loading and low tillage.

2) CO_2 stock emitted which describes CO_2 emitted to the atmosphere due losses of previously sequestered carbon and represents losses of carbon stock below a reference state. This inventory flow is analogous to biogenic CO_2 release through land use change.

Inventory flows for gains and losses of carbon shall be kept separate. All flows are considered per hectare of land, and a practitioner shall follow existing LCA practice to arrive at a final impact per kilogram of product (i.e., emission intensity). Inventory collection was identified through piloting as the most challenging aspect of including carbon sequestration in a farm-level LCA. Appendix B. has a compilation of identified models and a list of criteria to consider when choosing a model, as well as databases to provide support to practitioners.

6.1. UNCERTAINTY AND DATA QUALITY

Uncertainty and data quality should be considered with respect to the method used to measure or model inventory. Principles of data quality from ISO 14067 and the GHG Protocol (chapter 8)[7] shall be followed and specific data quality requirements depend on the context of the use of the LCA results (e.g., if used for reporting or public communication versus internal screening or hotspot identification).

The Guidance considers that Tier III models (e.g. process-based models combined potentially with sampling) or high-quality primary data measurements that go through a trusted third-party review provide the highest quality data, and lower tier methods

7 https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf

(e.g., IPCC Tier I) without third-party review are considered of lower quality. Primary data measurements of soil carbon can be highly uncertain and show significant spatial variation (FAO 2019), and expert judgement suggests that analytical measurement should not be considered by default as higher quality than modelling. Footprinting, or screening, which may use lower quality data shall consider the sensitivity of the results especially when providing decision-making guidance.

The data, models, and assumptions used (i.e., if generic or if from samples) shall be transparently communicated. If the footprint of carbon sequestration or loss of carbon stock represents more than 10% of a product footprint a practitioner shall consider and communicate the impact of uncertainty and quality of the data used, especially before any public result communication or decision making.

6.2. GENERAL PRINCIPLES OF INVENTORY COLLECTION

Pilot testing of the draft guidance demonstrated that inventory collection is a major challenge in accounting for carbon sequestration. As described in the previous section, higher tier models, i.e. process-based models that are combined (e.g. calibrated) with soil samples likely offer the most accurate estimate of expected changes in soil organic carbon, but this level of accuracy can be challenging to achieve and may not be needed depending on the application of the guidance. For example, if the guidance is being applied for public facing comparative product claims this high degree of accuracy is advisable, whereas an internal corporate carbon price may not require such rigor.

Annual losses and gains of sequestered carbon for the inventory shall be considered as stoichiometric CO_2 and consider soils and perennial biomass on a land area (e.g., per hectare). The Guidance suggests that the practitioner shall apply the concept of carried responsibility (Section 4) which requires considering inventory from years prior to account for changes with respect to the reference state. The reference state is defined as the stock amount just prior to the initiation of the responsibility window and is the state to which gains, and losses of carbon stock are considered and determines their climate relevance. In practice, considering the responsibility window implies that relevant inventory for the assessment year is the net carbon stock change each year since the responsibility window up until the assessment year.

The relevant inventory can be calculated simply as

$$\mathbf{S_{LCI} = S_{n_{assessment\ year}} - S_0} \qquad \textit{Equation 2A}$$

Where S_{LCI} is the net carbon stock relevant for the LCI, n is the assessment year, S_n is the total stock in the assessment year, and S_0 is the total stock of the reference state which is just before the initiation of the responsibility window. Alternatively, this can also be expressed as

$$S_{LCI} = \sum_{n=1}^{n=RW} Y_n = \sum_{n=1}^{n=RW} (Sn - Sn\text{-}1) \qquad \textit{Equation 2B}$$

Where n is each year within the responsibility window (RW), Y_n is the yearly net gain or loss of carbon stock, S_n is the total stock in each assessment year within a responsibility window, and S_{n-1} is the stock in the year prior to the assessment year, with S_0 as the reference state. Equation 2B is the sum of each year's annual gain or loss since the beginning of the responsibility window.

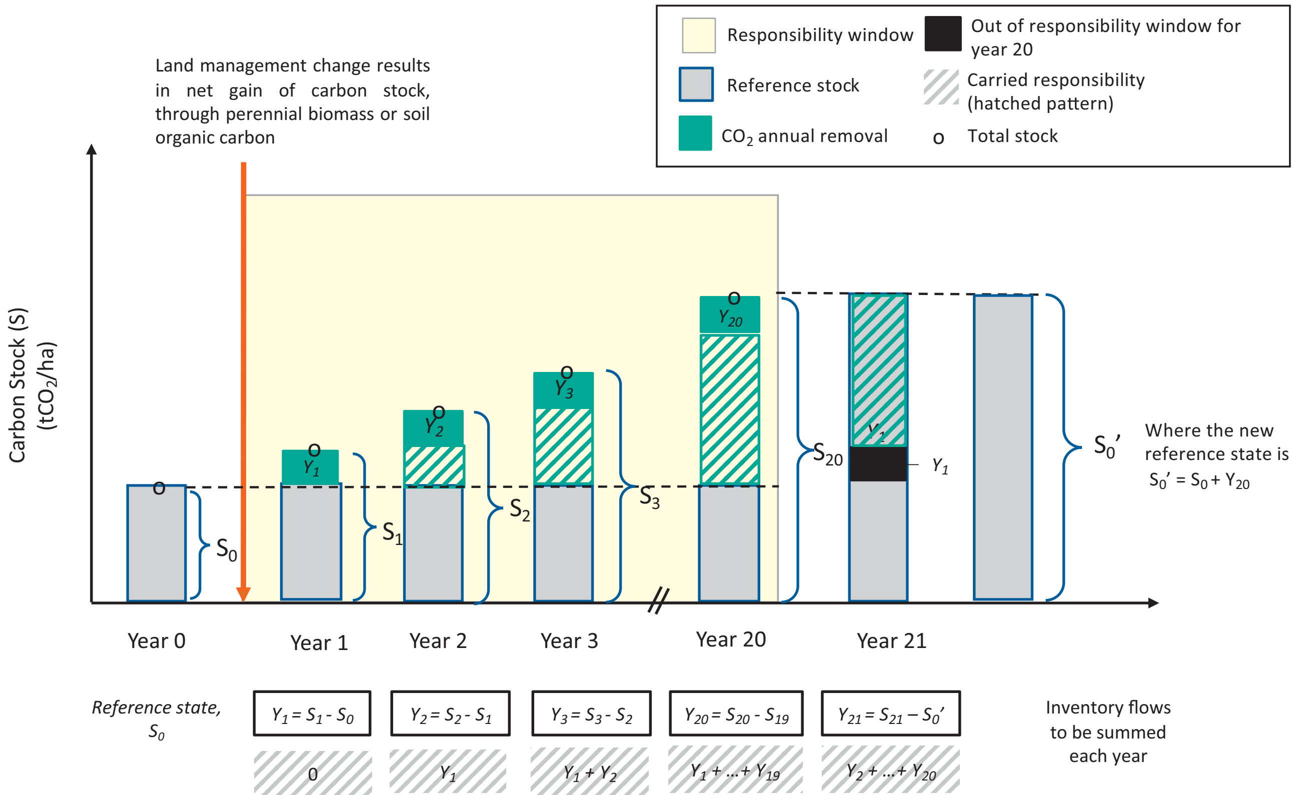

Figure 4. Schematic of inventory in a hypothetical example case where a land management change leads to net gains in carbon stock each year (Y) for 20 years. Relevant inventory as stored CO_2 is the sum of the annual stock gains throughout the responsibility window (RW). In this example, the responsibility window (RW) is set to 20 years. When moving forward in time the responsibility window shall shift just as it does in LUC accounting; in this example the relevant stock to inventory for year 21 is S0' which considers the change between stock in year 21 and stock in year 1 (the new start of the responsibility window as the assessment year minus 20 years). The total net change in carbon in the assessment year can be calculated as difference between the assessment year (S_{20}) and the reference state (S_0) (Equation 2A), or as the sum of the differences (i.e., Y_n) between the assessment year and the previous year (Equation 2B).

Figure 4 demonstrates relevant inventory since a land management change when there is only a gain in carbon stock. Note that gains in carbon stock can only be carried within a responsibility window (e.g., 20 years).

If there are gains and losses of carbon stock i.e., changes in stock during the responsibility window the practitioner shall separately inventory two separate potential flows of S_{LCI}

1) S_{LCI} as CO_2 stored which is when S_n > S0;
2) S_{LCI} as CO_2 stock emission which is when $S_n < S_0$; and

Figure 5 demonstrates a hypothetical example where there are gains and losses of carbon stocks over a period of time after the initiation of a land management change. The climate relevant flows are the CO_2 stored and the CO_2 stock emission and the carried responsibility of these inventories are visualised with respect to the responsibility window. In this example, in year 1 there is a gain of carbon stock due to change in practice (Y1). Unexpectedly, however, in year 2 the last year's stock gain is lost as a biogenic CO_2 emission and additional CO_2 stock is emitted (Y_2) that causes the total stock to go below the reference state. There is no carried responsibility of the previous year's storage because it is no longer stored in the system. In year 3, the practice again allows for building carbon stock (Y_3) and compensates for the carried responsibility of the stock emitted the previous year (Y_2) lost from the system. In year 4, the practice continues, stores a new amount of carbon (Y_4), and carries responsibility for the emissions and removals of the previous years 1, 2 and 3. In year 21 the stock has stabilized, and benefits and impacts related to carried responsibility begin to fall out of the responsibility window, such that the carbon stock that is "out of responsibility window" is no longer considered relevant for the inventory.

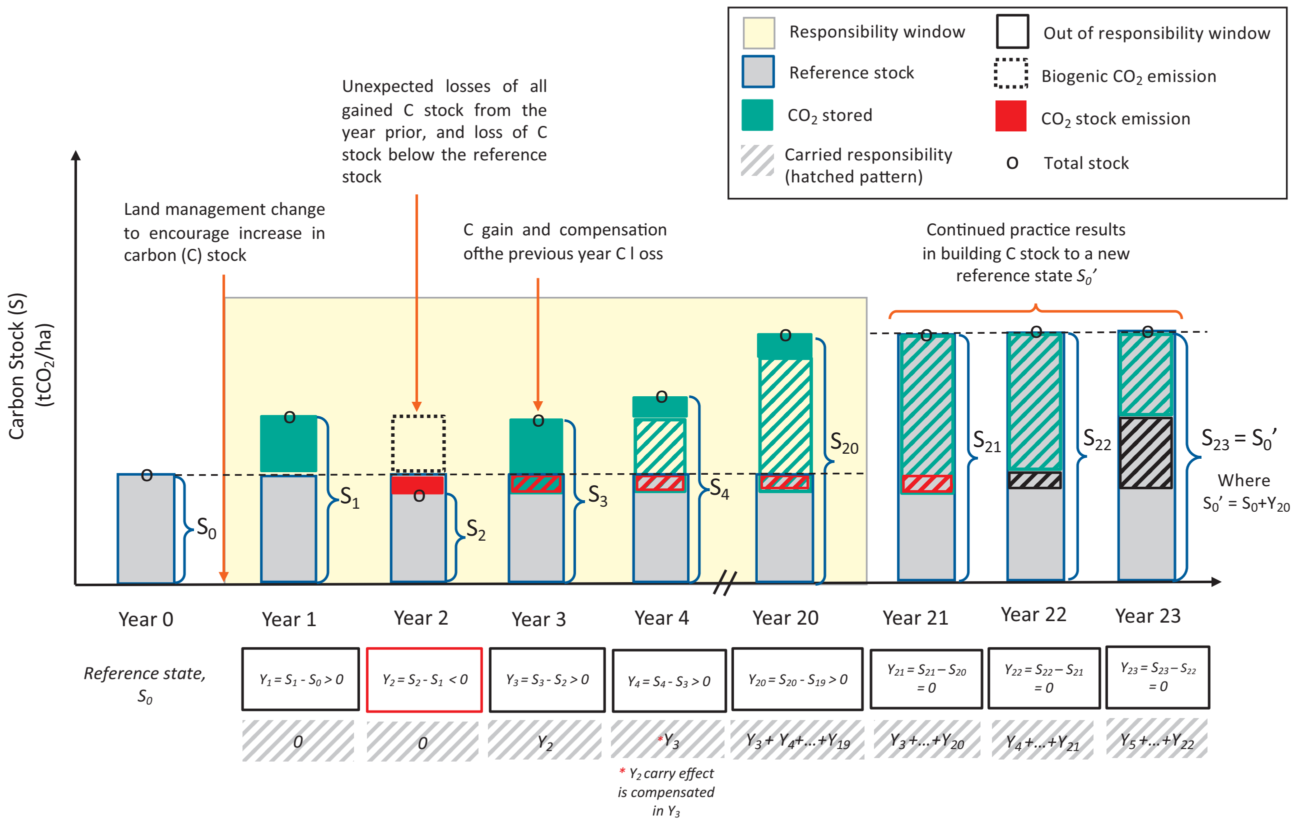

Figure 5. Schematic of inventory in a hypothetical example case where a land management change leads to variations in stock and thus CO_2 stored, CO_2 stock emission and biogenic CO_2 emission. Relevant inventory considers annual stock gains throughout the responsibility window (RW). In this example, the responsibility window (RW) is set to 20 years. When moving forward in time the responsibility window shall shift. Carried responsibility is shown for CO_2 stored and CO_2 stock emitted whereas the biogenic CO_2 emissions is not climate relevant so not carried forward in this example. This is an illustration of equation 2B.

It is good practice to inventory all flows into and out of a product system to ensure a mass balance, for example also the amount of biogenic CO_2 emitted (see Figure 2) when applying organic carbon to soils. It is consensus that such fast-cycling biogenic CO_2 releases (e.g.,

CO_2 releases from applied manures and composts, which is CO_2 that was recently removed from the atmosphere through photosynthesis) are assumed to have negligible climate impact (characterization factor of 0). (CH_4 and N_2O releases from manures and other organic matter shall be considered as per other LCA accounting guidance). Exceptions can be when peat material is used as compost because the carbon in peatland has been sequestered for hundreds (or thousands) of years, release of this carbon (whether through land management or through other means like composts) should be considered as a climate relevant CO_2 emission. Thereby the details of modelling this inventory flow are not covered in the current draft Guidance which focuses on the benefits and impacts of gains and losses of sequestered carbon.

Generally, when modelling carbon sequestration, the flow of biogenic CO_2 emission can be derived as the difference between the carbon added to the farm (e.g., through compost or manures) and the carbon that remains on farm in the form of soil organic carbon stock. Just as an example, it has been estimated a C sequestration of 10% of the total carbon added to the soil in a 100-year timeframe (Petersen et al. 2013).

The main inventory collection methods for land management change are:

- **Empirical soil organic carbon (SOC) models** (e.g., IPCC Tier I and Tier II models)
- **Process-based SOC models** (e.g., RothC, Century SOC Tier III models)
- **Measurements** (e.g., soil organic carbon samples)
- **Allometric equations for perennial biomass trees and hedges**, (e.g., IPCC Tier I methods, and academic literature), and related input variables needed (e.g., diameter at breast height and height)

In the Guidance the inventory is in reference to a unit area for a farm-level assessment. The practitioner is responsible for obtaining results per functional or mass unit according to existing practices in LCA, e.g., considering yield and any allocation methods.

6.3. LAND MANAGEMENT CHANGE

As accounting the influence of Land Use Change on land-based carbon accounting is detailed elsewhere, e.g., by the GHG Protocol Agricultural Guidance[8]8, this Guidance serves to fill a major knowledge gap regarding land management changes.

A land management change refers to a change in agricultural practices that influences the overall carbon stock for either soil or biomass on a farm. The change must occur within a land use category such that the land use does not change (e.g., till to no-till cropland, low-high input grassland). The relevant land uses as defined by the Intergovernmental Panel on Climate Change (IPCC) in this Guidance are cropland and grassland as well as wetlands (peatlands). A non-exhaustive list of land management changes that may be relevant to consider are listed in Table 1. The land management changes outlined in Table 1 may

8 https://ghgprotocol.org/agriculture-guidance

not always lead to change in carbon stock in every case, and thus each assessment must consider land management change on a case-by-case basis. Land management changes or continued practices beyond what is listed in Table 1 can be considered if there is evidence the agricultural system is not at steady-state and there is net carbon stock change due to a continuous practice.

The example inventory collection methods are suggested with respect to the availability of approaches - where Tiers I, II and III represent the degree of complexity of the methodology applied, regional specificity of model parameters and spatial resolution. Tier I is referring to more simple methods with default values based on aggregated empirical data. Tier II includes also simple methods with higher levels of data disaggregation (e.g., country level). Tier III includes more complex approaches based on monitoring and primary data collection (IPCC 2006) as well as innovative models that have not yet been documented by the IPCC. When data and resources are available and necessary for robust decision making higher tier methods are always recommended.

Table 1. Subset of land management changes relevant for dairy and beef sectors where carbon sequestration in soil or biomass or CO_2 emission may take place depending on the geospatial conditions and exact management practices.

Land management change	Relevant carbon pool	Example inventory collection method
Changing from till to reduced or no till with low, or high organic amendment (residues, compost, manure etc.)	Soil organic carbon	Tiers I, II, or III approaches can be applied.
Changing grassland management through selective planting	Soil organic carbon	Selective planting and grassland management are site-specific and highly variable; thus, Tier III methods may be required.
Reaching and controlling a carbon to nitrogen (C/N) equilibrium in amendments	Soil organic carbon	Tier I, II or III approaches can be applied.
Changing from intermittent bare soils to management with cover crops or crop rotation	Soil organic carbon	Specific scenarios of crop rotation are site-specific and highly variable; thus, Tier III methods may be required.
Changing from high intensity grazing to lower intensity grazing	Perennial biomass and/or soil organic carbon	Tier I, II or III approaches can be applied.
Changing to grazing practices such as adaptive multi-paddock grazing	Perennial biomass and/or soil organic carbon	Specialized grazing practices are site-specific and highly variable; thus, Tier III methods may be required.
Allowing regenerative growth for example of native species	Perennial biomass and/or soil organic carbon	Regeneration of native species is site-specific and highly variable; thus, Tier III methods may be required.

Land management change	Relevant carbon pool	Example inventory collection method
Changing from no or few trees or hedges to more trees and hedges	Perennial biomass and/or soil organic carbon	Adding trees and hedge is highly variable and site specific and thus Tier III methods (i.e., allometric equations sensitive to climate zone) may be required.
Changing drainage or flooding practices on peatland	Peat carbon	Managing peatland is site-specific and highly variable, thus Tier III methods may be required, although Tier I and II methods are available.

6.4. CONTINUOUS PRACTICE

In the case of continuous practice, the carbon stock lost/gained per year can be calculated as the difference between the current year's stock and the stock 20 years before divided by 20 years, i.e. $1/20 \times S_{LCI} = 1/20 \times (S_n\text{-}S_n\text{-}2_0)$. Following equation 2A, S_n in this case is the assessment year and S_{n-20} is 20 years prior to the assessment year or S_0.

Examples of situations where carbon sequestration can be accounted for continuous practice, even given no discrete event within the responsibility window:

Example 1: The responsibility window is set to 20 years. A peatland has been drained for the past 50 years and is continuing to lose carbon stock. The inventory for the assessment year is in relation to all carbon stock losses for the past 20 years.

Example 2: The responsibility window is set to 20 years. Due to geospatial conditions (e.g., cold temperature) a soil has not reached its maximum carbon stock even given 50 years of continuous management that adds carbon stock. The inventory for the assessment year should be based on a Tier III approach instead of Tier I and II default values as these assume a 20-year period for reaching equilibrium.

In the case of continuous practice, relevant inventory can be carried over the length of the responsibility window. This type of accounting allows for encouraging continued practices that sequester carbon in soils or biomass and discourages practices that are emitting carbon stock and can for example, deplete soil organic carbon or biomass.

6.5. INVENTORY FOR EMISSIONS AND STORAGE OF CO_2 FOR MINERAL SOILS

Inventory for soil organic carbon shall be calculated on per hectare or unit area basis for a farm for both mineral and organic soils. Production practices may vary across "parcels" (land sections) per unit area on a given farm or there may be different geospatial conditions (e.g., soil types) across a farm area. In this case each parcel (unique combination of land management, and geospatial conditions) would need to be accounted for, e.g., by a weighted average given the total farmland area. Similar to parcels, crop or pasture rotations (successive uses of the same land unit) can be handled by the proportion of the amount of time that certain crops or pastures occupy a field over a rotation period. For example, if maize occupies a field 20% of the time over the typical rotation, as a representative simplification this could be considered as 20% of the area of the field any given year. It is recommended to consider typical crop rotations based on a farmer's or expert knowledge and in the case of complex rotations to simplify as much as possible when doing the calculations. An example is given in Figure 6 of rotations on various parcels.

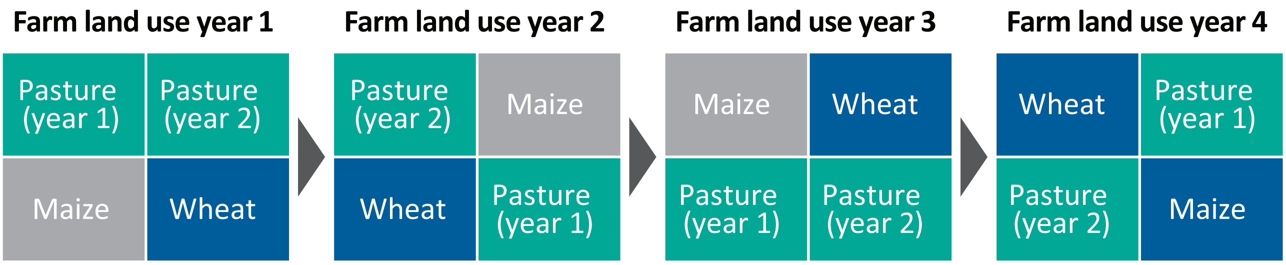

Figure 6. Rotations of various crops and pasture on land parcels.

When doing a calculation, a simplification of Figure 6 would be on any given year pasture is 50% of the land (8 out of 16 parcels occupied over the rotation), maize 25% and wheat 25% (4 out of 16 parcels occupied over the rotation).

The FAO Leap Guidance[9] provides comprehensive recommendations and steps to perform soil organic carbon sampling which are not covered in the Guidance. If there are resources available for measuring soil organic carbon, this is preferred to modelling, however given data variability soil organic carbon measurements may only be relevant over longer time scales that may not be practical for performing an LCA or GHG accounting assessment in any given year.

Specifically for mineral soils, the Guidance recommends estimating gains and losses of soil organic carbon in mineral soils using the information provided in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: AFOLU*. IPCC's decision tree can guide the user through the choice of the appropriate tiered method (see IPCC 19R, Vol4, Figure 2.4) where higher tier methods are considered in priority. As this Guidance is a first step in providing recommendations to include carbon sequestration in LCA we recommend using Tier III process models when a practitioner has access to resources (expertise, time, funds) that allow for appropriate and correct application of these models. Otherwise, the simpler Tier I and Tier II empirical models to consider soil organic carbon (SOC) are acceptable. For some innovative land management changes, modelling techniques may not be available.

9 http://www.fao.org/3/ca2934en/CA2934EN.pdf

Tier I and Tier II SOC change IPCC methods use the same model where Tier I uses generic, default values when the location is unknown, and the Tier II uses country or region-specific data and should be used in priority.

Applying either a Tier I or Tier II method begins with defining the parcel area with respect to a unique climate and soil type (e.g., based on the country). There may be more than one parcel area with unique climate and soil type combinations on a farm. A reference soil organic carbon stock (SOCREF) is then defined for each parcel from look-up tables (e.g., default vales in Table 6.2, IPCC 2006, Chapter 6) when a discrete event has occurred within the responsibility window. The reference stock is then multiplied by factors which are related to changes in land use (F_{LU}), management practices (F_{MG}), and organic amendment input (F_I) which results in a new reference stock (SOC_{REF}). The difference between the stocks is the change in SOC between the two states, leading to a gain or loss in carbon stock. If several soil types, climate regions, or management practices occur within the same farm, the method has to be applied to each of the sections separately and a “weighted average” of the parcels can be constructed.

Cover-crops are not explicitly covered by the empirical model, but the use of the F_{MG} factor “high without manure” enables the consideration of the increase of carbon inputs to the soil due to the cover crops or other residues or non-manure organic matter. The carbon in the cover-crops that may be removed e.g., due to harvesting is not considered sequestered material.

Soils are extremely complex systems and even more under livestock production. Soil organic carbon response to management practices will depend on the climate, type of soil and vegetation. In grazing systems additional factors influence the C accumulation in the soil, such as the removal of vegetation and input of faeces and urine, which are related to the intensity of grazing. Due to the many types of grazing practices and the diversity of plant species, soils and climates, the effects of grazing are difficult to predict. Thus, to date there is no consensus on the appropriate methodologies to estimate SOC stocks and changes under grazing land (FAO 2019).

Example
The following example illustrates the calculation of SOC change in grassland using **Tier I approach from IPCC guidelines** (2006). An overgrazed grassland in a temperate moist region and sandy soil is improved through a moderation on the grazing pressure. The responsibility window is set to 20 years.

Step 1
Goal: identify the type of soil (i.e., organic, or mineral) Example: In this case the soil is mineral.

Step 2

Goal: define the SOC reference value based on the climate and soil type, for each area of grassland being inventoried, IPCC Table 2.2 (IPCC 2006). Example: In this case one single area with a $\mathbf{SOC_{REF}}$ value at 0-30 cm depth of **71 tonnes C/ha**.

Step 3

Goal: Calculate SOC_0 at the beginning of the responsibility window (i.e., 20 years back). Select the original management practice F_{MG_0} and stock change factor for input of organic matter F_{I_0} (default vales in Table 6.2, IPCC 2006, Chapter 6). The multiplication of these factors by the SOC reference results in the "initial" soil carbon stock SOC_0.

F_{LU_0}: 1 (as there is no land-use change, it remains as a grassland)
F_{MG_0}: 0.95 (overgrazed or moderately degraded grassland receiving no management inputs)
F_{I_0}: not applicable (only relevant for improved grasslands)
$SOC_0 = SOC_{REF} \times F_{LU\_0} \times F_{MG\_0} \times F_{I\_0}$
$\mathbf{SOC_0}$ = 71 × 1 × 0.95 × 1 = **67.45 tonnes C/ha**

Step 4

Goal: Calculate $SOC_{REF'}$ which is the new equilibrium state after 20 years of this management practice. As in previous step, since there is no land use change, $F_{LU'} = 1$. Select the management practice $F_{MG'}$ and carbon input $F_{I'}$ (default vales in Table 6.2, IPCC 2006) related to the new practice. The multiplication of factors $F_{LU'}$, $F_{MG'}$, $F_{I'}$ by the SOC_{REF} results in the new equilibrium state of soil carbon stock $SOC_{REF'}$.

Example
$F_{LU'}$: 1 (as there is no land-use change, it remains as a grassland)
$F_{MG'}$: 1.14 (improve grassland with moderate grazing pressure)
$F_{I'}$: 1 (improved grassland with no additional management inputs)
$SOC_{20} = SOC_{REF'} \times F_{LU'} \times F_{MG'} \times F_{I'}$
$\mathbf{SOC_{20}}$ = 71 × 1 × 1.14 × 1 = **80.94 tonnes C/ha**

Step 5

Goal: Calculate the average annual change in SOC over the responsibility window (20 years).
Example
ΔSOC = $(SOC_0 - SOC_{20})$/ t = -13.49 t/ 20 = **-0.67 tonnes C/ha year**

Step 6

Goal: Convert the SOC into stoichiometric CO_2.

Example:
CO_2 removal= 0.67 × 44/12 = **2.46 tonnes CO_2 C/ha year**

The simplicity and ease of using the IPCC SOC equation lead to significant limitations. Depending on the study, there may be a need to monitor and verify soil organic carbon changes e.g., to justify the IPCC equations are reasonable to apply. As an example, these IPCC equations assume that less intense grazing managements lead to an increase in C stock. An increase in C stock cannot be guaranteed even with a change in grazing practice as it will depend on other co-practices and the local conditions e.g., temperature, soil, and vegetation characteristics (Contant et al. 2017). Furthermore, it is common practice in some regions to rotate between grazing and annual crops, and the SOC changes caused by such rotations are not explicitly accounted for in the IPCC equations. Several studies relating SOC to crop-pasture rotations, (Garcıa-Préchac et al 2004, Grahmann et al. 2020) have demonstrated gains in SOC, nitrogen concentration and crop yields compared to continuous cropping. However, to what extent such rotations and other grazing management practices affect soil properties is still an ongoing research. Future versions of the Guidance should consider the on-going research on various grazing management practices including crop-pasture rotations.

Summary of general considerations for Tier I & Tier II methods:

- Soil organic carbon (SOC) stocks reach an equilibrium state for a given climate, soil type and land management.
- When a change in land management practices is made, soil organic carbon stock will reach a new equilibrium after a transition time (D) (to steady-state) which is assumed to be equal to 20 years.
- The transition in soil organic carbon stocks is linear (i.e., it is the difference between two carbon stocks divided by 20 – see IPCC 19R Vol4, Equation 2.25).

In all cases, an inventory that is collected in units of soil organic carbon per unit area shall be converted to stoichiometric CO_2 by multiplying by 44/12 (the ratio of molecular weight of CO_2 to C).

6.6. INVENTORY FOR EMISSIONS OF CO_2 STOCK FROM DECOMPOSITION OF ORGANIC MATTER IN ORGANIC SOILS (PEATLANDS)

Wetlands include land that is covered or saturated by water for all or part of the year (e.g., peatland) and do not fall into the other land-use categories (forest land, cropland, grassland, and settlements (IPCC 2006, Annex 3A.5, Chapter 3, Volume 4)). Peatlands are important sinks of carbon as the rate of plant production and peat accumulation generally exceeds the rate of decomposition of the organic matter. However, changes in land use and unsustainable land management (e.g., continued drainage) convert peatlands from long-term carbon sinks into net sources of carbon emission.

There is no evidence that land use typical of beef and dairy supply chains (i.e., grazing, and annual cropland) can lead to increasing carbon sequestered in peatlands on a relevant timescale; however, there is evidence that management practices can decrease emissions. Drainage is a common management practice that has enabled farming on peatlands.

Drainage artificially lowers the water table and leads to an increase in greenhouse gas emissions (CO_2 and N_2O) through peat oxidation which can continue for centuries as long as they remain drained and oxidizing. In some cases, methanogenesis may take place in drainage ditches with a higher water table and rewetting with drainage of less than 20cm below the surface, CH_4 emissions can occur and should also be accounted for.

Various studies are looking into improving management practices, e.g., rewetting, on peatlands that can decrease emissions. One management practice is rewetting peatlands in such a way that agricultural practices can still be performed. Rewetting raises and restores the water table in peatlands, which then decreases CO_2 and N_2O emissions and techniques such as submerged drainage may also lower emissions.

To date, there are no standards for how the greenhouse gas emissions related to mitigation actions for agriculture on peatland should be monitored within the dairy sector. In this Guidance the presented approach for estimation of net loss of carbon stock and thus CO_2 stock emission is from the guidelines from IPCC 2013 supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. There are many studies that have been performed with more specific regional scope (Tiemeyer et al. 2020), for example the Tier II approach presented in Appendix A based on a study performed in The Netherlands (Lesschen et al. 2020). Given the climate relevance, it is highly likely that detailed data improvements will become available in the future, such as dynamic water level data, rate of surface lowering, and data on submerged drainage. If such detailed data are available for a specific region, it is recommended to include these data when estimating CO_2 and N_2O emissions from peatlands.

The IPCC guideline for wetlands presents an approach (Equation 3) for estimating annual on-site CO_2 emissions and removals from organics soils by multiplying the drained land area by an emission factor. For the Tier I approach, default emission factors are available in Table 2.1 from IPCC 2013 report. When more detailed data are available, Tier II can be applied based on country-specific emissions factors and finer classification for climate and management systems. In section 2.2 of the IPCC guideline (IPCC 2013) a detailed procedure for estimating the direct loss of soil carbon from drained organic soils is presented, as well as the annual off-site CO_2 emissions due to DOC loss and the non-CO_2 emissions.

$$\mathbf{S_{LCI} = \sum_{c,ns,d} EF_{c,n,d} \times \frac{44}{12}} \qquad \textit{Equation 3}$$

Where SLCI is the annual carbon stock loss (tonnes CO_2 stock emission) from drained peatlands in a land use category, EF is the emission factor (tonnes C/ha) for drained peatlands according to the climate domain c, the nutrient status n, and the drainage class d, 44/12 is the molecular weight ratio of CO_2 to carbon, and n is the number of years since the reference state. In this case the emission factor is already accounting for the annual changes between a reference state and the assessment year, and thereby this equation can be used directly in replace of equations 2A-B. In some cases, various combinations of parameters c, n, and d may occur on the same farmland. In this case, each parcel (unique combination of land management, and geospatial conditions) would need to be accounted for, e.g., by a weighted average given the total farmland area.

In the case of peatland, if there has not been a discrete event that qualifies as a land use change, the concept of the responsibility window may not be relevant as annual emissions may continue (depending on the management) – thereby the full annual emission depending on the management can be considered in the S_{LCI}.

6.7. INVENTORY FOR CO_2 STORED BY PERENNIAL BIOMASS

Like with soils, collecting inventory for perennial biomass is with respect to a reference state. If there is no perennial biomass existing prior to a discrete event (e.g., planting new trees or hedges, or allowing for new perennial regrowth in previous years) the inventory can be pragmatically calculated as the entire stoichiometric CO_2 stored in trees as the reference state for the biomass would be "0". If, however, there is previously existing perennial biomass on the farm which remains on the farm after a discrete event, it is not recommended to include within the inventory of a stock gain, because this stock is a part of the reference state. As an example, if a farm area is purchased that includes a forested area, the forested area is included in the reference stock and cannot be included as a climate-relevant inventory unless removed (in which case it is a climate impact). In this way, the responsibility window (RW) is valid, where if the RW = 20 and trees were planted more than 20 years ago, the guidance suggests to consider the continuous practice (section 5.4) for accounting. Likewise, if on-farm trees with age that is greater than RW are removed and the CO_2 released, this release shall be considered a climate impact analogous to calculations in land use change modelling. If burning or other biomass removal takes place before planting or allowing for regrowth or any other management practice, the emission of CO_2 from the removed biomass shall be included in the relevant inventory for CO_2 stock emission (S_{LCI}).

A calculation is provided for an example where there was no previous perennial biomass on a farm, and a discrete event takes place where 100 trees per hectare are planted.

Example
100 Birch *(Betula pendula Roth)* trees are planted on a hectare where there was no previous perennial biomass. The responsibility window is set to 20 years. The trees were planted in the year 2010 and it is now year 2020. Satellite imagery suggests there is no record of previously existing perennial biomass prior to 1995. The area is a temperate, moist climate. Given the discrete event and change in land management is related to tree planting, the reference state describes the state just prior to the discrete event of tree planting for which there was no perennial biomass and thereby the reference state carbon stock is S_0 = 0 kg CO_2 on the land area.

Step 1

Goal: "Look back" to gather historical information about the farm, the existing biomass, and the climate conditions in order to set the reference state and select the right allometric equations in the following steps.

Process: Identify the species existing in the farm and the number of trees per hectare. Check satellite imagery within the past 20 years. Identify the climate condition; climate conditions are usually sorted in three precipitation categories and climate type (tropical or temperate):

Table 2 - Precipitation categories and climate type

Precipitation > 2000 mm	Precipitation < 2000 & > 1000 mm	Precipitation < 1000 mm
Wet	Moist	Dry

Step 2

Goal: Select the most accurate allometric equation for each tree species present on the farm area.

Process: Select the allometric equation for each species (or type) of trees on the farm to calculate the "above ground biomass" (ABG). When selecting allometric equations, prioritize the tree species over the climate conditions. If tree specific species equation does not exist for your case, select a generic allometric equation such as the one proposed by the IPCC, for example the generic equation for estimating hardwood tree biomass from the IPCC Annex 4A.1 in temperate climate:

$$AGB = 0.5 + \frac{25{,}000 \times DBH^{2.5}}{DBH^{2.5} + 246{,}872}$$

Where:

AGB = Above ground biomass [kg] of dry matter

DBH = Diameter at breast height (1.3 m) [cm]

According to (Uri et al. 2012) studies of the carbon (C, the allometric equation for Birch in a temperate climate is:

$$ABG_n = (\alpha \times DBH^{\beta}) / 1000$$

Where:

AGB = Above ground biomass [kg] of dry matter of the tree during the assessment year at the age "n"

DBH = Diameter at breast height (1.3 m) [cm]

α = First parameter.

β = Second parameter

Table 3 - example site-specific tree parameters for 3 sites from Uri et al. 2012.

	α	β
Young trees (0-17 years old)	136.03	2.331
Middle age trees (18-45 years old)	182.94	2.309
Old trees (>45 years old)	121.24	2.503

Step 3
Goal: Gather physical parameters on the ground in order to increase the accuracy of the assessment.

Process: Gather the physical parameters of the assessed trees. It is possible to measure directly on the ground physical parameters such as the diameter or the height of a small number of trees or to do an average of a sample measured. If this process is possible, it will significantly increase the accuracy of the analysis. The physical parameters need to be estimated through an age-physical parameters relationship's equation and even sometimes, the age needs to be estimated.

In this example, the allometric equation requires only DBH. The measure needs to be done at 1.3 m height and is reported in centimeters.

Step 4
Goal: Calculate the AGB according to the gathered parameters.

Process: Use the selected allometric equation and the gathered physical parameters to calculate the AGB for biomass.

The DBH of the birch was measured and the value is 5 cm during the assessment year when the trees are 10 years old. It is then possible to calculate its AGB.

$$\mathbf{AGB_{10}} = \frac{136.03 \times DBH^{2.331}}{1000} = \frac{136.03 \times 5^{2.331}}{1000} = 5.79 \text{ kg biomass/tree}$$

Where the subscript "10" represents the age of the tree during the assessment year.

We can now estimate the total amount of aboveground biomass in the farm by multiplying by the density (100 trees/ha):

$$\mathbf{AGB_{10}} = 5.79 \frac{kg}{tree} \text{ x } 100 \frac{trees}{ha} = 579 \frac{kg}{ha} = 0.579 \frac{Mg}{ha}$$

Step 5
Goal: Calculate the BGB according to the calculated AGB.

Process: For consistency we recommend when it is possible to use the same source for the quantification of above ground and below ground biomass. Uri et al. 2012 would be

19.3% of the total biomass fraction is below ground biomass. However, for ease-of-use we provide here the IPCC equation from Annex 4A.1 (in Mg/ha) for below ground biomass (BGB):

$$\mathbf{BGB = exp\ (-1.0587 + 0.8836 \times ln(AGB) + 0.2840)}$$

Where:
BGB= root biomass in Mg/ha of dry matter
AGB= aboveground biomass in Mg/ha of dry matter

Step 6
Goal: Obtain the final S_{LCI}.

Process: Sum needed carbon stocks, subtract S0 and convert to stoichiometric CO_2.

It follows that

$$\mathbf{Total\ biomass = AGB + BGB}$$

$$\mathbf{Total\ biomass = 579\ kg\ ABG\ /\ ha + 284\ kg\ BGB\ /\ ha = 863\ kg\ total\ biomass/ha}$$

Multiply by the proportion of carbon (i.e., 47%) in the biomass:

$$\mathbf{C_{(mass\text{-}ha)} = 863 \times 0.47 = 406\ kg\ C/hectare}$$

The relevant reference state $S_{0\text{-biomass}}$ is “0” as there was no perennial biomass pre-existing. Because there are only gains of carbon stock, and a responsibility window of 20 years is considered, equation 2A shall be applied.

In kg stoichiometric CO_2/ha the relevant LCI for the assessment year, S_{LCI} (kg CO_2 stored-year/ha), is estimated by:

$$\mathbf{S_{LCI} = S1_{15} - S_{0\text{-biomass}} = 1{,}489\ kg\ CO_2/ha}$$

Where $\mathbf{S_{10} = C_{mass\text{-}ha} \times \frac{44}{12}}$

Being 44/12 the ratio between the molecular weight of CO_2 and C, and where the relevant stock S_{10} is 10 years after the initiation of the responsibility window the relevant reference state.

If we wish to have S_{LCI} (kg CO_2 stored-year/tree) we just need to divide by the density (100 tree/ha) to obtain a value per tree of 14.9 kg CO_2.

When the number of trees in the assessment year does not equal the number of trees planted, we should define if the dead trees are replaced or not. If they are replaced the density stays the same. However, if there is no replacement and there is gapping due to mortality then the following equation must be used:

$$\mathbf{N = N_{planted} - N_{died}}$$

When the mortality rate is known we can then use the following equation:

$$\mathbf{N = N_{planted} - (N_{died} \times \%_{mortality})}$$

7 INVENTORY CHARACTERIZATION

The Guidance suggests two characterization factors for carbon sequestration accounting, 1) for releases (emissions) of sequestered carbon that represents losses of carbon stock from a reference state and 2) for gains (storage) of sequestered carbon above a reference state which is assumed to be entirely reversible.

The relevant inventory to be characterized for CO_2 stored are gains of carbon stock (biomass or soil organic carbon) with respect to the reference state; and the relevant inventory for CO_2 stock emitted to be characterized are losses of carbon stock with respect to the reference state. No new guidance is provided for fast-cycling biogenic CO_2 emission (i.e., losses of carbon from composts, crop residues, leaf litter etc.), and the characterization factor (as is standard practice) is suggested to be 0 kg CO_2eq/kg biogenic CO_2 emitted year. Exceptions may include using peat or other land-based organic carbon that has been sequestered for hundreds of years as compost or soil amendment in which case emissions should be considered with a characterization factor of 1 kg CO_2eq/kg CO_2 emitted-year.

To obtain final results for the climate relevancy the calculation is

$$\mathbf{I = S_{LCI} \times CF} \qquad \textit{Equation 3}$$

where the climate impact or benefit (I) in units of kg CO_2eq is the inventory SLCI multiplied with the relevant characterization factor (CF). The relevant characterization factors for each inventory flow are summarized in Table 4. Figure 7 demonstrates an example LCI and characterized results.

Table 4. Characterization factors recommended in the guidance for emitted CO_2 and stored CO_2, inventoried as net losses or gains of carbon stock in a given year Sn from a reference state S0.

Inventory Flow	Inventory units	Characterization factor	Adjusted characterization factor given a 20-year responsibility window
S_{LCI} when $S_n < S_0$	kg CO_2 stock emitted-year	1 kg CO_2eq/kg CO_2 stock emitted-year	0.05 kg CO_2eq/kg CO_2 stock emitted-year (expires after 20 years)
S_{LCI} when $S_n >$ $_{S0}$	kg CO_2 stored-year	-0.01 kg CO_2eq/kg CO_2 stored-year	-0.05 kg CO_2eq/kg CO_2 stored-year (expires after 20 years)

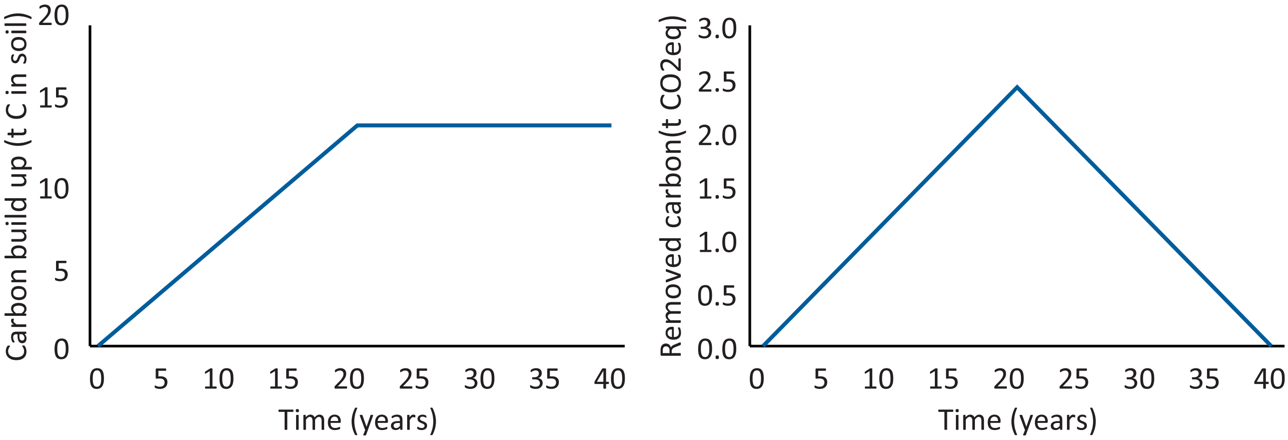

Figure 7 Carbon stock gain through time in tonnes (t) of carbon (C) in soil for a grazed field that reaches a steady state at year 20 and the accounting of the removed carbon in terms of carbon dioxide equivalent considering 5% accounting factor and carrying the neutralization benefit over a responsibility window of 20 years (e.g., at year 40 no additional neutralization benefits can be claimed and any lost stock would be treated as an emission).

As a clarification, when there is a loss or emission of carbon stock as CO2, but carbon stock remains above the reference stock S0, then there is no reported emission (this follows standard practice for biogenic carbon emissions). This lost carbon could reduce the amount of sequestered stock and thus should not be claimed as a removal. In practice, this means that biogenic CO_2 emissions from manures, composts, and residues are not considered as CO_2 emissions that are climate relevant. This is because such flows reflect carbon that was already in the atmosphere, removed through photosynthesis, stored intermittently in soils or biomass, and then emitted from the farm through biophysical processes.

Such fast-cycling CO_2 is assumed to have a negligible impact on climate and tracking this emission is irrelevant for climate goals.

For gains of sequestered carbon, the characterization factor is a linear coefficient of -1/100 kg CO_2eq/kg CO_2 stored-year (i.e., the climate benefit for a year of stored CO_2), otherwise expressed as -0.01 kg CO_2eq/kg CO_2 stored-year or -1% credit (benefit) of net gain in carbon stock i.e., when the carbon stock in any given year (Sn) is larger than the reference stock (S0). This characterization factor was chosen to provide a robust, scientifically sound, yet easy-to-apply method. This characterization factor has been suggested by the International Reference Life Cycle Data (ILCD) documentation by the European Commission (JRC-IES 2010) and reviewed by other authors (Brandão et al. 2019; Levasseur and Brandão 2012). Using this characterization factor allows that 1) there is no over-estimation of benefits if there is future reversal of carbon sequestration, and 2) given the responsibility window there can be continuous credit for keeping carbon stored.

8 OTHER CONSIDERATIONS AND NEXT STEPS

8.1. APPLYING THE APPROACH IN LCA SOFTWARE

If using software, and assuming there are no changes to the software architecture and no new characterization factors added, it is generally recommended that LCI for carbon stock gains and losses (i.e., kg CO_2 stored and kg CO_2 stock emitted) are adjusted by the final adjusted characterization factor suggested by the Guidance in order to enter in the software as a CO_2 flow which will be characterized (multiplied) by 1 kg CO_2eq/ kg CO_2 (the same characterization factor as fossil CO_2 and biogenic CO_2 emissions released via land use change). This can be added to the software as an equation with a comment also with respect to when the database entry is applicable (e.g., in a 20-year period after a management change). As an example, where potential reversibility is considered for an assessment year, LCI for carbon stock gains shall be adjusted by -0.05 kg CO_2eq/kg CO_2 stored-year with a 20-year responsibility window and entered as a CO_2 flow analogous to land use change then would be multiplied simply by "1" by the software. As another example, if the database entry will be used in a way where there is no farm-level information, and the database entry is to represent a farm with a given perpetual practice at any given time – a pragmatic approach would be to estimate the total carbon sequestration possible for a given practice as negative CO_2eq, e.g., -20 tCO_2eq due to SOC gain over 20 years, and then divide over 100 years to obtain a yearly average.

8.2. OTHER DECISION-MAKING CONSIDERATIONS

Carbon sequestration is one potential consequence of land management. Land management that improves carbon sequestration in soil or trees, may have other benefits such as improved water and nutrient retention, animal welfare, as well as improved long-term yields in the cases where land degradation is prevented (although there may be short term yield reductions in some cases). In some cases, if tillage is reduced other interventions such as mechanical, chemical, or biological removal of pests and weeds may be required to ensure crop yield. This Guidance does not cover benefits or impacts that may result from changing practices to improve carbon sequestration. Considering co-occurring benefits, impacts, and any unintended consequences of changing land management should be considered prior to any decision making.

8.3. NEXT STEPS

As more scientific research on carbon sequestration develops and organizational climate targets become more common, the collective understanding of this topic and how to apply in decision making will strengthen. This Guideline is a first step in developing a consensus on how to account for carbon removals through carbon sequestration in LCA and carbon footprinting – with a specific focus on the dairy and beef sector. The Guideline should be iterated and tested e.g., through pilot projects and application in corporate climate strategy projects, and potentially tested and challenged also by other sectors (e.g., related to perennial crops and forestry). Future versions of the Guidance should consider what extent of monitoring and verification may be needed to apply the IPCC equations with reasonable certainty. This Guideline serves as a steppingstone for other guidelines and frameworks (e.g., Product Environmental Footprinting and GHG Protocol) to update their accounting rules and methodologies for carbon removals accounting. As we look to the future, greenhouse gas accounting should be helpful to align with net zero targets and therefore considerations e.g., of maximum carbon sequestration potential and distance to this target may be an important next step in setting strategy.

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APPENDIX A

Responsibility windows

The advantages and disadvantages of the different reponsibility windows (i.e., 20, 50 and 100 years) were submitted for public consultation (Table A1).

Table A1. Trade-offs of different responsibility windows

Responsibility window (Years)	Adjusted characterization factor (kg CO_2eq/kg CO_2 stored-year)	Advantages	Disadvantages
20	5%	- Aligned with LUC accounting - Realistic time period for agricultural land management - Feasible time period to find data on past changes	- Overestimates benefits of carbon sequestration if reversed in the future (i.e., adjusts the characterization factor of 0.01 to be 0.05 kg CO_2eq/ kg CO_2 stored-year) - Would not capture changes in practices occurring prior to 20 years before the assessment year
50	2%	- Somewhat realistic time period for agricultural land management - Offers a per-year benefit of carbon sequestration aligned with some scientific evidence (e.g., Moura-Costa method)	- Not aligned with LUC accounting - Difficult to find data to document the past
100	1%	- Offers a time period aligned with GWP100 - Captures practices that have occurred within the past 100 years	- Not aligned with LUC accounting - Is a time period too long to be relevant for inspiring changes in land management - Difficult to find data to document past changes - Impacts and benefits are small per year which discourages changes

Peatland example

As one example of a region specific study in The Netherlands, Lesschen et al. (2020) presents a Tier II approach for calculating CO_2 stock emission and N_2O from drained peatlands (Equations A1 and A2). This method uses an expected surface lowering, which depends on the groundwater level class, the presence of sandy or clay topsoil layer, and the mineral richness (trophic level) of the peat as documented from (Kuikman, Akker, and Vries 2005) (Table A2).

Equation A1 is used to compute CO_2 emissions (kg CO_2/ha) from peat soils in The Netherlands and is used in the national emission inventory (Arets et al., 2019):

$$\mathbf{S_{LCI} = C_{stock\ emitted} \times \frac{44}{12}}$$

$$\mathbf{C_{stock\ emitted} = S_{mv} \times \rho_{so} \times fr_{os} \times fr_{c} \times 10^{4}} \qquad \textit{Equation A1}$$

Where SLCI is the stock emission stoichiometric CO_2 (kg CO_2 stock emitted/hectare and where
S_{mv} = rate of annual surface lowering (m year^(-1))
ρ_{so} = bulk density of immature peat (kg m^(-3))
fr_{os} = organic matter fraction in peat (-)
fr_{c} = carbon fraction in organic matter (-)

The rate of annual surface lowering (S_{mv}) is available in Table A2. Default values cited by Lesschen et al. (2020) to calculate CO_2 emission in The Netherlands are 140 kg soil m-^{3} for bulk density of peat (ρ_{so}), 0.8 for the organic matter fraction of peat (fr_{os}), 0.55 for the carbon fraction in peat (fr_{c}), and the factor 44/12 is used to convert C into CO_2. The 104 conversion factor is to convert from m^2 to hectares.

Equation A2 enables calculating the annual relevant S_{LCI} for N_2O emissions from peatlands in The Netherlands (tonnes CO_2eq/ha):

$$\mathbf{S_{LCI} = ((C_{stock\ emitted} \times 14/12) \times 0.02) \times \frac{44}{12} \times 298} \qquad \textit{Equation A2}$$

Default values to calculate $C_{stock\_emitted}$ by Lesschen et al. (2020) are listed with Equation A1. The factor 14/12 was to convert from carbon stock to nitrogen stock and the factor 44/28 was used to convert N into N_2O. In this case the characterization factor for global warming potential is 298 kg CO_2eq/kg N_2O. The practitioner shall ensure that the characterization factor applied for N_2O is aligned with the rest of the LCA.

The advantage of the Lesschen et al. (2020) equation over IPCC general equation is that it provides a way to include farm management practices (e.g., different intensities of drainage or rewetting) by including the water table depth. However, caution has to be taken when applying the equation to peatlands outside of The Netherlands and should be checked by experts. Generally, country or region-specific approaches are preferred.

Table A2. Data, estimated C/N values of the underground and ground level drops of peat soils used for agriculture in The Netherlands (mainly grassland)

Top soil	Trophic level[1]	C/N	Poorly-drained		Reasonable-Drained		Well-drained		End-total
			Rate of annual surface lowering (mm/yr)	Surface (ha)	Speed yearly ground level drop2 (mm/yr)	Surface (ha)	Speed yearly ground level drop2 (mm/yr)	Surface (ha)	Surface (ha)
Clay layer	Eutrophic	20	3	16149	8	17250	13	531	33929
	Mesotrophic	20	3	12780	8	22294	13	2863	37935
	Oligotrophic	40	3	9421	8	10480	13	416	20315
Peaty2	Eutrophic	20	6	16668	12	16846	18	206	33719
	Mesotrophic	20	6	18668	12	31607	18	7169	57443
	Oligotrophic	40	6	8688	12	10054	18	1168	19911
Peat colonial	Mesotrophic	20	3	148	8	3184	13	4771	8102
	Oligotrophic	40	3	27	8	760	13	2256	3041
Sand layer	Mesotrophic	20	3	1365	8	3370	13	1318	6051
	Oligotrophic	40	3	415	8	1450	13	836	2700
End total				84325		117291		21531	223147
%				37.8		52.6		9.6	100

[1] Gives an indication of the mineral richness of the peat. Oligotrophic peat has grown under nutrient-poor conditions while mesotrophic and eutrophic have grown under moderate to nutrient-rich circumstances.

[2] Peaty soils are soils with a thin layer of peat (less than 40 cm)

Reference: Table 5 From: Kuikman, P.J., J.J.H van den Akker & F. de Vries, 2005. Emission of N_2O and CO_2 from organic agricultural soils. Alterra, Wageningen, Alterrarapport 1035-2. 66 blz.; 23. tab.; 5

APPENDIX B

Identified carbon sequestration models and databases

MODELS

MODELS	SOURCE
CANDY	Franko et al., 1995
CCB	Franko et al., 2011
Century	Parton et al., 1992
Daycent	Parton et al., 1998
DNDC	Li et al., 1994
EPIC	Izaurralde et al., 2006
NDICEA	Van Der Burgt et al., 2006
ORCHIDEE	Krinner et al., 2005
Roth C	Coleman & Jenkinson
C Tool	Taghizadeh-Toosi et al., 2014
IPCC	IPCC, 2019 https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch05_Cropland.pdf
ICBM	Andrén & Katterer, 1997
CESAR	iTech & Université Gustave Eiffel
SOMM	Chertov & Komarov, 1997
Yasso15 soil carbon model	FMI, monitored by Liski et al.
DAISY	University of Copenhagen - Agrohydrology group
App SOC plus	http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1665-64232016000200135
TRIPLEX-GHG	Wang et al., 2017
TRIPLEX-MICROBE	Zhang et al., 2017
FullCAM	Australian Government - Department of Industry, Science, Energy & Resources
CARBINE Soil Carbon Accounting Model: CARBINE-SCA	Forest research
Ex-Act	https://www.fao.org/in-action/epic/news-and-events/detail-events/en/c/1417610/

Criteria to consider when choosing a model

- Development team (private, public, etc.)
- Published scientific articles or other case studies
- Model validation method
- Application validity (e.g., geography, soil types, climate zones)
- Amount and type of required input data
- Type of output data and applicability to the study
- Availability of model (license, udpates, etc.)

- Type of model (process based, empirical)
- Temporal scale and resolution (e.g. per month, year)
- Spatial scale and resolution
- Soil depth
- Nitrogen interactions and emissions

DATABASES	SOURCE
WISE soil property database	https://www.isric.org/explore/wise-databases
LUCAS	https://esdac.jrc.ec.europa.eu/projects/lucas
Global soil organic carbon estimates	https://esdac.jrc.ec.europa.eu/ESDB_Archive/eusoils_docs/Other/EUR25225.pdf
Circumpolar Soil Carbon Database (NCSCD)	https://snd.gu.se/en/catalogue/study/ecds0148#:~:text=The%20Northern%20Circumpolar%20Soil%20Carbon,the%20northern%20circumpolar%20permafrost%20regions.
GloSIS	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-soil-organic-carbon-map-gsocmap/en/
European Soil Database: ESDB	https://esdac.jrc.ec.europa.eu/content/european-soil-database-v20-vector-and-attribute-data
CIAT global soil organic carbon sequestration potential	https://ciat.cgiar.org/global-soil-carbon/
Harmonized world soil database	https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/ru/
SOTWIS database	https://www.isric.org/projects/harmonized-continental-soter-derived-database-sotwis
U.S. General Soil Map (STATSGO2) by State	https://datagateway.nrcs.usda.gov/Catalog/ProductDescription/GSMCLIP.html
ASRIS	https://www.asris.csiro.au/
Soil Grids	https://www.isric.org/explore/soilgrids

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