Agricultural Systems 227 (2025) 104361

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Review

Harmonizing soil carbon simulation models, emission factors and direct measurements used in LCA of agricultural systems☆

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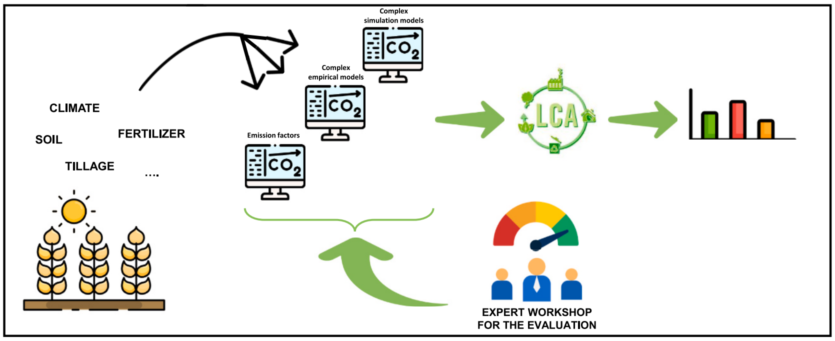
HIGHLIGHTS

- Improvement of soil carbon accounting estimation tools needed for inventory phase in life cycle assessment.
- Reviewed existing estimation tools to develop a coherent harmonization approach for soil C change.
- The results show that high applicability was related to low accuracy and vice versa.
- With sufficient data DNDC or CropSys models are preferred, alternatively IPCC Tier 1 is easy to use.
- New challenges for soil carbon accounting will require temporal and spatial differentiation.

GRAPHICAL ABSTRACT



☆ This article is part of a Special issue entitled: 'Agricultural LCA methods' published in Agricultural Systems.

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https://doi.org/10.1016/j.agsy.2025.104361
Received 11 November 2024; Received in revised form 31 March 2025; Accepted 24 April 2025

ARTICLE INFO

Editor: Paul Crosson

Keywords:
LCA
Cropping system
Livestock system
Soil CO_2 emissions
SOC change

ABSTRACT

CONTEXT: The increasing demand for animal products, coupled with the need to reduce greenhouse gas (GHG) emissions from livestock production, highlights the urgency for effective mitigation strategies for livestock systems, including the cropping systems. Soil organic carbon (SOC) sequestration, a crucial approach for reducing atmospheric GHG concentrations, is often underrepresented in Life Cycle Assessments (LCA) of agricultural systems, largely due to methodological challenges in accurately accounting for soil carbon dynamics.
OBJECTIVE: The objective of this study was to evaluate soil carbon simulation models, emission factors and direct measurements used in LCA, with the aim of developing a harmonized approach for including soil carbon change in agricultural LCAs. The goals were to: i) assess soil carbon simulation models, emissions factors and direct measurements used in LCAs of agricultural systems; ii) evaluate the strengths and weaknesses of these models; iii) provide recommendations for LCA practitioners; and iv) identify areas for future methodological improvements.
METHODS: A systematic review of soil carbon simulation models, emission factors and direct measurements used in LCAs of agricultural systems was conducted, obtaining 263 relevant articles from an initial pool of 29,151. In addition to direct measurements, fifteen soil carbon simulation models and three methods based on emission factors were identified and categorized into three tiers based on complexity and data requirements. A modified Delphi participatory process was used to evaluate each method against established criteria through expert workshops.
RESULTS AND CONCLUSIONS: The results showed an inverse relationship between applicability and accuracy of methods, making the choice of methodology critical to achieving high-quality LCA results. Recommendations emphasize selecting methods based on objectives and data availability, while being aware of the effect of the initial soil carbon level and the assessment time period when using soil carbon simulation models. In addition, this study identified current methodological challenges in assessing soil C dynamics in LCA of agricultural systems.
SIGNIFICANCE: This research provides a foundation for improving LCA practices and supports better decision-making in mitigating climate impacts of agricultural systems.

1. Introduction

Agriculture, forestry and other land use sectors contribute 22 % of the total greenhouse gas (GHG) emissions which comprised 59 Gt of CO_2-eq in 2019, worldwide. Thus, all economic sectors should reduce GHG emissions, including agriculture (IPCC, 2022). Meanwhile, animal product demand is forecast to increase in the future due to the growing population and economic prosperity (Godfray et al., 2018). This growth implies an expansion of livestock numbers and a corresponding increase in feed crop cultivation, linking livestock and cropping systems in their contribution to overall GHG emissions. Globally, around 2.5 billion hectares of farmland, representing about half of all agricultural land, are dedicated to producing feed for livestock (Mottet et al., 2017). To compensate for this increase, there is a need for practices that reduce total atmospheric emissions (Kane and Solutions, 2015). Carbon sequestration, which is the removal and temporary storage of carbon from the atmosphere either in the permanent vegetation or soil, is seen as a potential pathway towards climate change mitigation. (Brandão et al., 2013; Don et al., 2024; Rodrigues et al., 2023). Soil organic carbon (SOC) is the main terrestrial carbon sink for reducing GHG emissions, with potential additional benefits, such as improving soil health, fertility, and agricultural production (Rodrigues et al., 2023; Wang et al., 2022). Soils constitute the largest pool of terrestrial organic C (~1500 Pg C at 1 m depth; 2400 Pg C at 2 m depth (Paustian et al., 2016)), which is three times the amount of CO_2 currently in the atmosphere (~830 Pg C) and 240 times current annual fossil fuel emissions (~10 Pg) (Batjes, 2014; Ciais et al., 2013; Lal et al., 2021; Le Quéré et al., 2016). Therefore, increasing net soil C storage by even a small percentage over a large area represents substantial C accumulation potential. Soil carbon dynamics approach an equilibrium depending inter alia on soil types, climate, and management practices. Management strategies can increase SOC content, but the ability of the soil to sequester carbon is constrained by factors such as soil carbon saturation limits and diminishing returns over time (Powlson et al., 2014; Stewart et al., 2007).

Land management changes, such as crop selection influence SOC dynamics through associated management practices, inputs, and residue characteristics, which in turn affect soil carbon sequestration. Practices like switching from annual to perennial crops and vice versa and waste and residue management can enhance SOC levels (Petersen et al., 2013). Changes in land use can also contribute to SOC changes. These changes occur either directly within the production system or indirectly as a consequence of production activities elsewhere (Planton, 2013). Thus, land use change (LUC) and sustainable soil management are crucial for the effective sequestration of terrestrial organic carbon (Rodrigues et al., 2023).

CO_2 emissions from soils are evaluated mostly with regards to land management changes (e.g. tillage, fertilisation) (Pelaracci et al., 2022) and LUCs (from and to grassland/ cropland/ forest), following Intergovernmental Panel for Climate Change (IPCC) classification (McConkey et al., 2019; Ogle et al., 2019b; Ogle et al., 2019a). Short-term biogenic carbon fluxes, such as occur within annual crops are not considered in GHG accounting. For example, during the night, vegetation acts as a carbon source through plant respiration, while decomposition of crop residues in the soil releases carbon into the atmosphere. In addition the yearly storage of carbon in agricultural products, by means of photosynthesis is not included, as products are used, and thereby oxidated to CO_2 within a few years. Soil CO_2 flux can be used as an indicator of changes in soil carbon stocks, reflecting either net emissions (carbon release to the atmosphere) or net sequestration (carbon uptake from the atmosphere). When accounting for CO_2 flows in agro-ecosystems it is important to assess which management practices and land-use changes can mitigate greenhouse gas emissions and enhance soil carbon sequestration in agricultural systems, including but not limited to livestock production. (Grossi et al., 2019; Jiang et al., 2023; Sykes et al., 2019).

Life Cycle assessment (LCA) can be used to assess environmental impacts of livestock systems and products. It has also been effective to assess land management practices and their impact on environmental performance of a cropping and grassland systems (Goglio et al., 2014; Rotz, 2018; Zaher et al., 2013). In order to improve the environmental assessments in the livestock systems, it is important to consider the interaction between cropping and livestock systems.

The importance of soil C sequestration and soil CO_2 is poorly reflected in current LCAs (Goglio et al., 2015; Petersen et al., 2013), since the majority of studies have not included soil C sequestration in the overall GHG estimations, mainly due to methodological limitations (Brandão et al., 2019). However, recently a few LCA studies have attempted to include soil C changes - using mainly modelling (Goglio et al., 2018a; Jensen et al., 2024; Knudsen et al., 2019; Lefebvre et al., 2021; Petersen et al., 2013). Jensen et al. (2024) showed a 14 % reduction in the carbon footprint of cabbage and Knudsen et al. (2019) showed a 5–18 % reduction in carbon footprint of milk from different production systems due to inclusion of soil carbon changes in the LCA. Goglio et al. (2018b) demonstrated through direct observation that soil carbon sequestration accounted for 62 % of the total global warming potential (GWP) mitigation across the cropping systems and crops analysis. This highlights the significant role that soil carbon plays in the overall GHG budget of cropping systems and crops, underscoring the necessity of incorporating these factors into future LCA methodologies (Goglio et al., 2015; Paustian et al., 2016).

Furthermore, the use of satellite-based methods, such as remote sensing and spectral analysis, is emerging as a promising solution for assessing soil carbon content at larger scales, providing more detailed and continuous data on spatial variations in soil carbon. These methods, together with field measurements, can enhance the accuracy of carbon sequestration estimates in LCA models. (Morais et al., 2023; Pouladi et al., 2023).

In addition, there is an increasing need to assess livestock systems, taking into account present and future climate (Godfray et al., 2018; Willett et al., 2019). Improved LCA methodologies can capture systems' effects, crop-livestock interactions and circular economy aspects (Costa et al., 2020; Goglio et al., 2017; Grossi et al., 2019; Van Zanten et al., 2018) with a focus on C sequestration and GHG emissions (FIL-IDF, 2022; Goglio et al., 2023).

Grasslands play a crucial role in carbon sequestration, significantly contributing to GHG mitigation. Despite this, they remain understudied compared to croplands, even though they represent ~70 % of global agricultural area (ITPS, F, 2015), which is 25 % of the Earth's ice-free land surface (FAO, 2019), and store 28 % to 37 % of the terrestrial SOC pool (Paustian et al., 2016) which implies that they play a significant role in the global carbon and water cycles (Herrero et al., 2016; Wang and Fang, 2009). Despite their importance, grasslands present unique challenges for soil carbon modelling and assessment and most of the existing carbon tools were primarily developed for annual crops, and their ability to simulate SOC dynamics in grasslands is often limited (Ehrhardt et al., 2018). These ecosystems are particularly complex and difficult to investigate because of the wide range of management and environmental conditions they are exposed to (McSherry and Ritchie, 2013; Senapati et al., 2016; Soussana et al., 2010), leading to a large variability in their CO_2 source/sink capacity, such as the frequency and intensity of foliage removal and its fate (grazed on site or mowed and exported) (Herrero et al., 2016; Jérôme et al., 2014), difficulties in measuring grassland productivity, spatial variability due to grazing and animal excreta (Dlamini et al., 2016; Oates and Jackson, 2014), and complexities in direct and accurate measurements of small changes in SOC stocks over short time periods in response to different management practices (Allen et al., 2010; Arrouays et al., 2012). Models like DNDC, DAYCENT, Century provide valuable tools for representing these processes, but their accuracy can still be enhanced due to the inherent complexities of grassland ecosystems. Therefore, advancing our understanding and improving the modelling of grasslands are essential for developing effective carbon management strategies that contribute to global sustainability goals. While the DNDC model simulates multiple soil carbon pools, its performance is highly sensitive to input data quality and often requires extensive site-specific calibration and data requirement to run (Del Grosso et al., 2020). The latter is a major limitation also for the DAYCENT model (Del Grosso et al., 2020). In contrast, the Century model, valued for its simplicity and low data requirements, can simplify soil processes but operates on a monthly time-step thus may not adequately estimate crop yields and residue inputs or reflect local management practices (Goglio et al., 2015).

Several harmonization attempts for calculating GHG emissions were carried out in sectors other than agriculture (Segura-Salazar et al., 2019; Siegert et al., 2019), wines (Jourdaine et al., 2020), citrus fruit sector (Cabot et al., 2022) or food waste, proposing to better integrate between LCA and soil science (Morris et al., 2017) and for soil N_2O emissions in agricultural systems (Goglio et al., 2024). However, the integration and recommendation of harmonized estimation tools specifically for assessing soil carbon changes (both emissions and sequestration) within agricultural systems was not previously published, even though recent guidelines have been proposed by the Food and Agriculture Organization (FAO, 2020; FAO, 2016a; FAO, 2016b; FAO, 2016c; FAO, 2016d; FAO, 2016e),

Considering the growing urgency to integrate soil carbon dynamics into LCA methodologies for agricultural systems, this review aims to harmonize existing soil carbon estimation tools. The objectives were: i) assessing soil carbon simulation models, emission factors and direct measurements used in LCA of agricultural systems; ii) evaluate strength and weaknesses of these estimation tools; iii) providing recommendations for LCA practitioners; iv) identifying the need for methodological improvements in future research.

In this paper, we address the urgent need for a harmonized framework to assess soil carbon changes in agricultural systems LCA. Our approach goes beyond existing reviews through assessing both simulation models, emission factor-based approaches and direct measurements, and applying a multi-step Delphi process to define robust evaluation criteria.

2. Methodology

2.1. Screening and review procedures

A systematic review of the existing literature was conducted to provide a comprehensive assessment on how LCA methodologies account for soil C changes in LCA of agricultural systems. To achieve this, a review protocol was developed (Fig. 1), describing the search and screening process including an iterative process of article selection based on restrictive criteria.

For the selection of scientific literature, publications in English in scientific journals or published by the FAO or the European Commission, were first retained.

A literature search was performed in Scopus, Web of Science and Google Scholar databases. Key words employed include "LCA", "Life Cycle Assessment"," life cycle analysis", "soil", "emissions", "carbon dioxide", "CO_2", "carbon sequestration", "GHG", "greenhouse gas", "C dynamics", "carbon", "livestock", "wheat", "maize", "grass", "barley", "oat", "soy", "faba beans", "alfalfa", "clover", "sorghum", "Rye", "Ley", "soil emissions", "soil carbon", "soil organic matter", "feed", "fodder", "farming system", "farm", "dairy", "cattle", "sheep", "pig", "poultry", "goat", "milk", "egg", "chicken", "cow", "husbandry", "crop soil emissions", "wheat soil emissions", and 29,151 papers were found with these keywords. The search was limited to the 2012–2022 period in the following research areas: Agriculture; Agriculture or Soil or Animals or Cattle or Dairying or Crop production or Animal feed or Animal Husbandry or Swine or Livestock or Chickens or Poultry.

Selected publications focused on methods relevant to LCA that are linked to crop-livestock systems or their components, specifically applicable to crop-livestock systems. Papers related to rice, plastic, biofuel, and bioenergy were excluded as not fully related to the livestock sectors. Papers on biogas without any link to feed, insect, fish were also disregarded.

Further screening was carried out to analyse the evaluation of the accessibility of the articles, the language and the region. Documents prior to 2012 and inaccessible ones were excluded (1175 documents). A further selection was based on the content of the abstracts, if relevant to

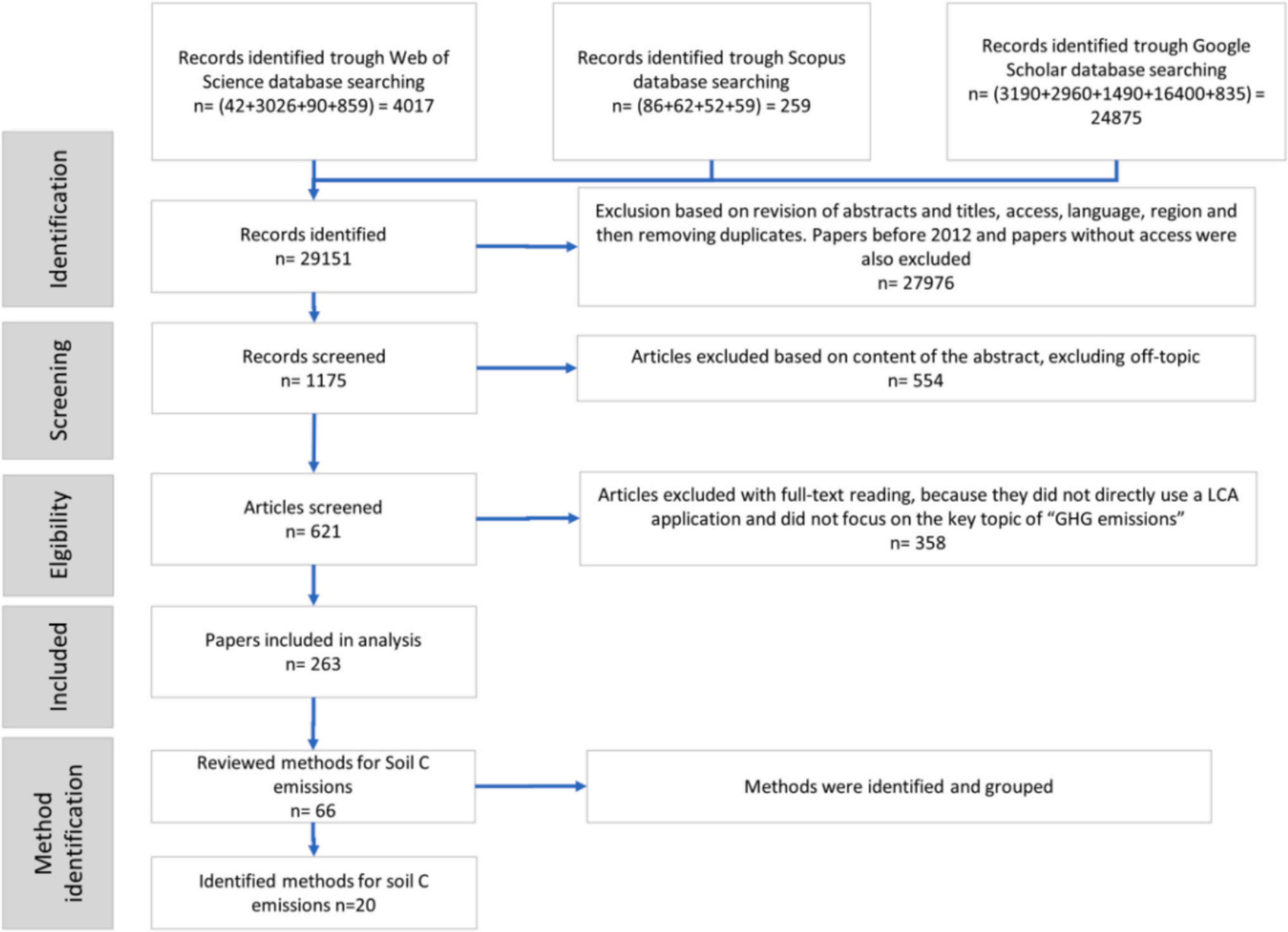

Fig. 1. Methodological steps of the literature search process for soil CO_2 emission estimation in LCA of crop-livestock systems.

the work. As a final step, the remaining 621 articles were subject to a complete reading of the text to exclude those not directly relevant. This iterative process brought the number of articles to 263, of which 66 related to soil C. After further grouping and method identification, only 20 were retained.

2.2. General criteria and specific criteria selection

A harmonization participatory approach based on a modified Delphi method was used to identify key topics and evaluation criteria for LCAs of crop-livestock systems. The criteria were identified through a literature review and 19 workshops with experts from different disciplines and nationalities. These participatory approaches have fostered consensus among participants. The workshops were organized to elicit expert knowledge and record key findings, arguments and observations. Further details are provided in Goglio et al. (2023).

Initially, the priority topics on which to base the research were identified. An anonymous survey among LCA experts was conducted via Google Survey, to select the criteria used to evaluate and compare the suitability of different soil carbon estimation tools in LCA of agricultural systems, which were then refined through expert discussions to align with the methodological harmonization of LCAs for livestock systems and products. Definitions and scales have been adapted for some criteria to ensure rigor and consistency in the evaluation of LCA estimation tools.

The criteria that emerged from the discussion were: i) Transparency and reproducibility (Comprehensive documentation and mechanisms that allow reviewers to verify/review all data, calculations, and assumptions); ii) Completeness (Relationships between quantification of the environmental impact (material/energy flows and other environmental interventions) and adherence to the defined system boundary, the data requirements, and the impact assessment methods employed); iii) Fairness and acceptance (Level playing field across competing products, processes and industries); iv) Robustness (Associated in the RACER framework the following sub criteria of providing a defensible theory, Sensitivity, Data quality, Reliability, Consistency, Comparability, Boundaries); v) Applicability (Ability of the method to be used by a wide range of LCA practitioners).

The selection of specific criteria was carried out with a combined approach involving both literature and expert knowledge. A group of experts composed of three or four individuals, as in previous studies evaluating the implementation of LCA (Testa et al., 2022), was involved in the selection and refinement of the specific criteria (Goglio et al., 2023). The group worked on the specific assigned topic in three to five workshops. Four specific criteria related to soil C accounting estimation tools in crop-livestock systems were discussed: i) Adaptability to different soil types (If the method can be applied to different soil types, e.g. peat soils, coarse and medium/fine textured mineral soils); ii) Adaptability to different land uses (If the method can be applied to different types of land use, e.g. grassland and cropland); iii) Adaptability to different climates (If the method can be applied to different climates, e.g. temperate and boreal climates); iv) Accuracy (The ability of the LCA methods to capture the daily changes and the long-term dynamics of CO_2 emissions; it also takes into account the temporal horizon over which the soil CO_2 emissions occur (Brady and Weil, 2002; Lal and Stewart, 2018)).

A complete list of criteria definitions and detailed scoring used in the Delphi assessment can be found in Appendix A.

It was assumed that the LCA practitioner has sufficient expertise to adopt the methodology and that observations have been carried out with a protocol. Further details can be found in Pelaracci (2024).

2.3. *Data processing*

Following the workshops with experts in which the general and specific criteria on which to evaluate the estimation tools were selected, a targeted discussion was held in which all the experts of subgroup 5 of the PATHWAYS project (15 experts from 12 research institutions and universities across Europe) evaluated all the estimation tools examined, using the chosen criteria.

Each expert evaluated each estimation tools for each criterion, assigning a score from 1 to 3 (or 1 to 4 based on the scale on which the criterion was evaluated). The overall method assessment was reviewed in several group workshops ($n = 19$) which have been progressively evaluated. When disagreement was found among experts, this was resolved through targeted discussions and reassessment of the methods, following previous research (Goglio et al., 2023).

From the data obtained, the mean, the minimum and maximum values were calculated for the scoring results for each different estimation tools and for each criterion (Fein et al., 2022).

3. Results and discussion

3.1. *Quantitative results*

The soil carbon simulation models, emission factors and direct measurements used in the LCA of agricultural systems satisfied most of the general criteria, with the exception of applicability (average score across all 5 criteria $>$2.72 on a scale of 1–3 except for completeness (1–4)). Average values were slightly higher than those found in the assessment for N_2O emission calculation methods in agricultural LCA (average score $>$ 2.4) (Goglio et al., 2024). Despite higher average scores for general criteria, the applicability average score was lower (1.47 on average with a range from 1 to 3) (Fig. 2) compared to N_2O emission methods (1.7 on average with a range from 1 to 3). More than 64 % of estimation tools reviewed in this research scored more than 3, indicating that the LCA estimation tools reviewed here have sufficient transparency, completeness, fairness, acceptance, and robustness, in contrast to Goglio et al. (2024) where 94 % of the methods scored 2 or higher but only a smaller percentage (22 %) scored 3 or higher. This comparison illustrates that although both types of methods generally scored well for most criteria, soil carbon tools encounter distinct challenges, particularly in applicability, that are not as pronounced in N_2O methods. However, 55 % of the estimation tools scored 1 for applicability, indicating that many estimation tools applied for soil carbon change have very limited applicability (Fig. 2). Based on the estimation tools assessed, only the IPCC Tier I approach (for details see appendix B) scored 3 for applicability (Aalde et al., 2006).

For the specific criteria, the soil CO_2 emission estimation tools assessed had an average score above 2.28 on a 1–3 scale. However, for adaptability to soil types, land uses, and climate conditions, more than 96 % of the estimation tools scored higher than 2. Except for adaptability to different climates, where the average scores were low ($<$ 2.2 on a 1–3 scale). The methods for N_2O emissions also achieved high average scores (2.4 on a 1–3 scale) (Goglio et al., 2024). In contrast, only 18 % scored above 2 for accuracy, with only three methods scoring 4 (i.e., CropSys, DNDC, and Delta LCA, see section appendix B) (Li et al., 1996; Stöckle et al., 2012a; Wiedemann et al., 2016a). Therefore, the majority of soil CO_2 emission estimation tools (82 %) reviewed here were assessed as having low accuracy within livestock systems (Fig. 2). This is similar to the findings in Goglio et al. (2024) for N_2O emission methods.

To improve clarity and facilitate the comparison of methods, Table 1 summarizes the average scores assigned to each estimation tool evaluated in this study. The tools are categorized into three tiers according to the IPCC methodology, from simple empirical (Tier 1), complex empirical models (Tier 2), to complex simulation models and direct measurements (Tier 3). Detailed descriptions and tier classifications for each tool are provided in Appendix B.

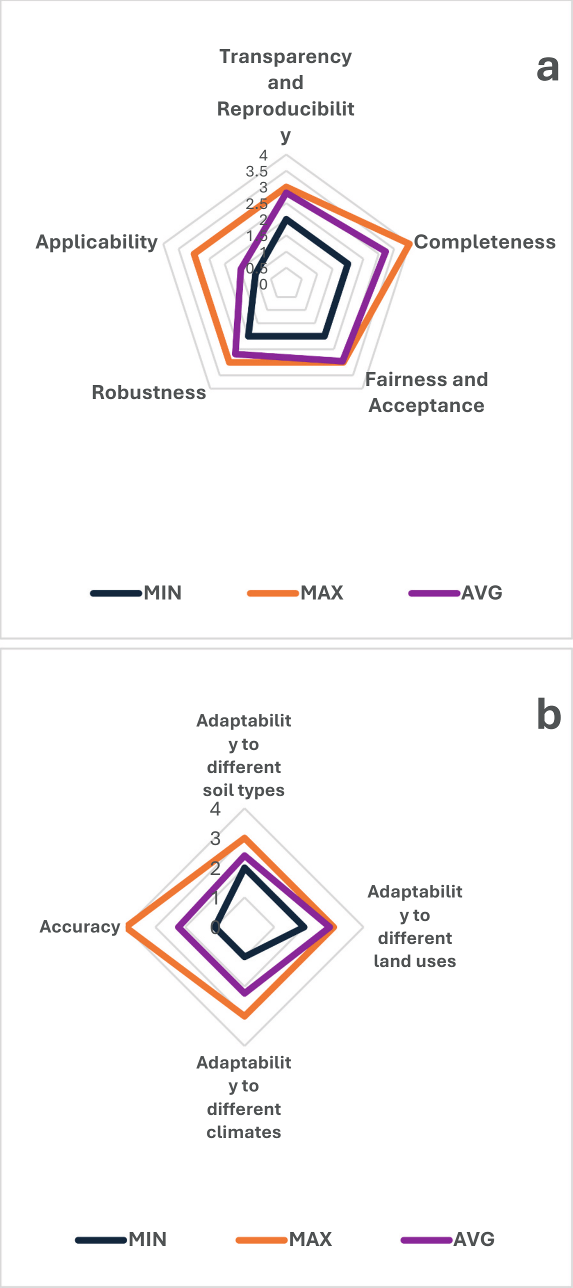

Fig. 2. Results obtained for the five general criteria (a) and four specific criteria (b) for the LCA estimation tools used to assess soil CO_2 emissions simulation models, emission factors and direct measurements. Orange colour indicates the maximum value obtained, grey colour the minimum value and blue colour the average value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

From the results obtained, approximately the same limitations for both soil carbon accounting estimation tools and N_2O emission methods were observed.

3.2. *Identified key methodological issues*

The soil carbon estimation tools, scored high with regards to the general criteria ($>$2.68 for all the general parameters except

Table 1
Summary of scores for general and specific criteria of soil carbon estimation methods.

	General criteria					Specific criteria			
Method name	Transparency and Reproducibility	Completeness	Fairness and Acceptance	Robustness	Applicability	Adaptability to different soil types	Adaptability to different land uses	Adaptability to different climates	Accuracy
Emission factors (simple empirical) (Tier 1)									
Delta LCA	3	3	2	3	2	3	3	2	4
IPCC 2006 Tier 1	3	4	3	2	3	2	3	3	1
IPCC 2006 Tier 2	3	3.5	3	3	1.5	2	3	1	2
Basic process or complex empirical models (Tier 2)									
AMGv2	2	4	3	3	2	2	2	2	2
SOCRATES	3	4	3	3	2	3	3	2	2
C-Tool	3	4	3	3	2	2	3	2	2
IMAGE	2	2	3	3	1	3	3	3	1
IPCC Tier II SS	3	3	3	3	1	2	3	2	2
Roth C	3	3	3	3	2	2	3	2	2
Yasso	3	3	3	2	1	3	3	2	2
ICBM	3	3	3	3	2	2	3	2	2
Complex simulation models and direct measurement (Tier 3)									
CANDY	3	3	3	2	1	2	2	2	2
CENTURY	3	3	3	3	1	2	3	2	2
CropSys	3	4	3	3	1	3	3	2	4
Direct measure	2	3	3	2	1	3	3	3	3
DNDC	3	3.5	3	3	1	3	3	3	4
TEM	3	3	3	2	1	2	3	2	2
TRIPLEX	2	3	3	3	1	3	3	3	2
FullCAM	3	3	3	3	2	2	3	2	2
MIN	2	2	2	2	1	2	2	1	1
MAX	3	4	3	3	3	3	3	3	4
AVG	2.78	3.28	2.94	2.72	1.47	2.44	2.89	2.22	2.28

applicability). However, most of the estimation tools(59 %) assessed have a low applicability (average value below 1.50). This can be related to the complexity and large data requirements of the estimation tools, limiting their applicability, as previously reported (Goglio et al., 2015). Most of the assessed soil carbon estimation tools (96 %) considered climate, soil characteristics and land use, however only three estimation tools(DNDC, CropSys and Delta LCA) scored a high level of accuracy (>3), while the average for accuracy was quite low (<2). Furthermore Delta LCA can only be employed in Australian conditions (Wiedemann et al., 2016b). All these estimation tools are based on several pools of carbon and are able to capture soil C dynamics (Li et al., 1996; Stöckle et al., 2012b; Tuomi et al., 2009; Wiedemann et al., 2016b). As highlighted in previous papers, it is often difficult to achieve high data quality for soil C assessments which is often the case for site-dependent LCA, site-generic LCA, consequential LCA and anticipatory LCA (Dale and Kim, 2014; Goglio et al., 2019; Potting and Hauschild, 2006). The most common estimation tools used to assess soil C is therefore the use of IPCC Tier 1 methodology, which has often been considered inadequate as it provides simplified estimates based on categories and poorly reflects local conditions, as previously reported (FAO, 2018; Goglio et al., 2015), which are relevant for LCA of agricultural systems (Camargo et al., 2013; MacWilliam et al., 2014). However this methodological compromise is highly dependent on the objectives and the system boundary of the assessment, in agreement with the ISO standards (ISO, 2006a, 2006b). The IPCC Tier 1 methodology scored very high in terms of applicability (3).

Grassland systems present unique challenges for soil carbon accounting due to their inherent spatial and temporal variability, combination of plant species, and complex interactions with management practices such as grazing, mowing, and fire regimes (Zhou et al., 2022; Eze et al., 2018; Bai and Cotrufo, 2022). Recent research highlights the critical role that plant and soil biodiversity play in mediating the impacts of climate change and promoting SOC storage in grasslands (Bardgett et al., 2021; Yang et al., 2019). In particular, the formation of microbial necromass carbon, mineral-associated organic matter (MAOM), and particulate organic matter (POM) is influenced significantly by biodiversity, land management practices, and restoration efforts, thereby complicating soil carbon modelling (Bai and Cotrufo, 2022). The estimation tools which scored higher in accuracy are typically crop-based and may not fully capture this complexity in grassland system. Such crop-based tools generally simplify these multispecies interactions and often underestimate spatial and temporal heterogeneity common in grassland ecosystems (Li et al., 1996; Stöckle et al., 2012a; Tuomi et al., 2009; Wiedemann et al., 2016a). The DNDC model, when used to simulate intercropping over the long-term (approximately 50 years), well simulated the yield and N uptake of the intercropping system under different N management scenarios, however, the yield and associated N uptake of one of the crops in the mix was underestimated (Zhang et al., 2018). On the other hand, grassland systems are multispecies systems, where each species has its own agronomic characteristics, which is often reflected in high spatial and temporal variability (Klumpp et al., 2010; Paustian et al., 2016). Furthermore, grassland yields and residues usually lack quantification at the farm level, making soil C dynamics more difficult to quantify through modelling (FAO, 2019).

Beside data quality and the type of methodology to be selected, another key factor is the LCA practitioner expertise. Independently of the method chosen, the inappropriate use of the soil CO_2 emission estimation tools could cause potential biases in the assessment, as previously discussed for soil C in agricultural LCA and for GHG mitigation (Goglio et al., 2015, 2019). A key aspect to be considered in the application of estimation tools for the assessment of soil carbon are the equilibrium dynamics of the soil C which affects the magnitude and duration of soil C sequestration (Paustian et al., 2016) going from one equilibrium reflected in the initial carbon content and depending on historical practices towards a new equilibrium based on the assessed farming practices. This equilibrium can be achieved with different timing and is dependent on the interaction between farm management, soil and climate characteristics (Gan et al., 2014; Goglio et al., 2015; Petersen et al., 2013). Indeed several models, such as DayCent or IPCC Tier 2 Steady State, require a spin-up period to stabilize the soil C dynamics (Pelletier et al., 2024; Uzoma et al., 2015). In DNDC a 5–10 years spin-up is required (He et al., 2021; Perlman et al., 2013). Thus, the initial soil carbon (reflecting historical practices) and the time perspective in which the assessments are done are indeed affecting the results of the soil CO_2 emission estimation tools.

Measurements if not appropriately carried out can also lead to biases (FAO, 2019). However, they are still a valuable data source for LCA, if properly carried out, despite their low applicability at a large scale due primarily to cost and time constraints (FAO, 2019; Goglio et al., 2018b).

3.3. LCA methodological issues related to scale and objectives

The importance of soil C change is poorly reflected in current LCA methodologies (Goglio et al., 2015; Koerber et al., 2009), partly due to challenges related to selecting appropriate temporal horizons and adequately considering initial soil carbon content (Brandão et al., 2013; Brandão et al., 2019). Some LCA studies have included changes in soil carbon based on a 100 years' time perspective to align with GWP100 (Knudsen et al., 2019; Knudsen et al., 2014) and other LCA studies have used temporal horizons of 30 years or less (Hörtenhuber et al., 2010; Röös et al., 2010; Halberg et al., 2010; Hillier et al., 2009; Mila i Canals et al., 2008; Gabrielle and Gagnaire, 2008), although the temporal horizon used is not explicitly stated in all studies. Most of the estimation tools discussed, do not fully consider the temporal effects of carbon balance in soil, which are relevant to climate change (Brandão et al., 2013, 2019; Bui et al., 2018; Plevin, 2017).

Two critical challenges in accounting for soil carbon changes in agricultural LCA are establishing a clear baseline (initial soil carbon content) and determining an appropriate time perspective for assessments. Among the main uncertainties and discussions regarding the inclusion of soil carbon changes in LCA of agricultural products is the achievement of a new equilibrium (Petersen et al., 2013). Essentially, the shift to a new agricultural practice will lead to a change towards a higher or lower level of soil organic matter, eventually stabilizing at a new equilibrium. The carbon in soil organic matter is not “stable” but undergoes constant turnover, and net changes in soil carbon will balance between what is sequestered and what is emitted (Oberholzer et al., 2014). Furthermore, some simple procedures such as Tier 1 IPCC use a 20-year temporal perspective to accumulate the total change in SOC between practices (time to equilibrium), however, the period for this to occur may actually be 30 years, or even 100 years (Goglio et al., 2015). As a result, modelling only 10 or 20 years, the rate of accumulation of SOC, and thereby the consequences for GHG emission calculation, may be greatly exaggerated. Therefore, the chosen temporal perspective for assessing carbon sequestration or recovery time is crucial. A well verified process-based agroecosystem model can be used to estimate the period to equilibrium and the dynamics of SOC change over time. Other approaches include using complex empirical models combined with a carbon decay model, such as the Bern Carbon Cycle Model, which allows the integration of temporal aspects of soil carbon changes by accounting for CO_2 degradation and atmospheric decline. This method highlights the significance of the time perspective chosen, with substantial differences observed across 20, 100, and 200-year horizons, thereby impacting the results and comparability in LCA applications (Petersen et al., 2013). Initially the rate of SOC change between practices is high with gradual decrease over time, usually following first order decay towards a new equilibrium (Smith et al., 2012).

Our assessment revealed that current carbon balance estimation tools, which have a significant impact on LCA results, show a dichotomy between high accuracy and low applicability, or vice versa (e.g., low accuracy but high applicability). Estimation tools with high applicability only roughly account for the interaction between soil, time, and management. Although the drivers of this interaction are well known, quantifying their effects on soil carbon is often difficult (Paustian et al., 2016), because of long-term equilibrium dynamics and soil variability (FAO, 2018; Loubet et al., 2011; Petersen et al., 2013). Most of the analysed empirical estimation tools consider constant management, while in reality, farmers may change crop and grassland management practices annually, thus influencing the outcomes on soil carbon dynamics (Goglio et al., 2017). However, the individual contributions of crop management practices to various carbon pools are usually not evaluated in the long term. Only a few attempts have been made, for example, using the Bern Carbon model (Petersen et al., 2013), the DAYCENT model (Nguyen et al., 2022) or DNDC model (Jiang et al., 2023).

Two critical challenges in including soil carbon estimates in climate impact assessments are establishing a clear baseline (initial soil carbon content) and determining an appropriate time perspective. In agricultural LCAs, accurately defining this baseline is crucial because the initial soil C content is strongly influenced by historical management practices and often determines modelling outcomes. If an arable crop rotation of grain legumes and catch crops is introduced on a soil with high carbon content due to a historical practice of dairy cow grazing in a grassland system, the soil carbon content will presumably decrease. On the contrary, the same rotation applied to a soil with low C content, resulting from intensive wheat production and straw removal, would presumably increase the soil C stock. This interaction between historical management (which establishes the baseline) and any proposed changes is fundamental to the modelling process. When assessing the impact of a change in farming practices, a comprehensive approach is to first simulate the current set of practices to determine the baseline soil carbon content and then simulate the effect of the proposed new practices using that baseline as a starting point. This process in two steps ensures that the influence of historical practices is properly accounted for in the LCA results. Furthermore, the time perspective for the assessments is decisive since the transition from one equilibrium to another can span 20 to 100 years, with the most pronounced changes occurring at the beginning. A short assessment period may, therefore, exaggerate the effects if the total change in SOC from a management practice is expected to occur within this limited timeframe. These considerations underscore the importance of carefully defining both the baseline and the assessment period when modelling soil carbon change.

Future LCA research should therefore develop methodologies which encompass the correct level of details to capture the interaction between soil C dynamics and crop management on one side and on the other side the extensive application of the estimation tools in itself also by agricultural consultants and farmers with a more limited level of expertise. This methodological choice should be carried out in agreement with the LCA objectives.

3.4. LCA methodological recommendations

From the analysis of the current LCA estimation tools, some preliminary recommendations can be made regarding the suitability and application of estimation tools when undertaking an agricultural system LCA.

To accurately assess soil C dynamics within a temperate climate, a time perspective of at least 20 years is required. This should be considered or, at the very least, estimated based on the best available knowledge (Goglio et al., 2015; Petersen et al., 2013), as such a “spin-up” period is necessary for most models. Furthermore, it is important to be aware of the shifts from one equilibrium to another and the potential decisive effect on the results of the historical practices reflected in the initial soil carbon content, when using estimation tools for accounting of C exchanges. For site-specific assessments (e.g., at the farm level), agroecosystem models such as DNDC or CropSys are preferred. If less detailed input data is available, the IPCC 2019 Tier 2 steady-state methodology can be employed. For broader, site-dependent or site-generic assessments, or when large-scale evaluations are needed, the use of Tier 2 methodologies such as the IPCC 2019 Tier 2 steady-state method or simplified carbon models like C-TOOL and ICBM is recommended (Andrén and Kätterer, 1997; Ogle et al., 2019a; Petersen et al., 2013). In cases of very limited information, or when data quality cannot be ensured or expertise is lacking, the IPCC Tier 1 methodology may be used (Ogle et al., 2019b). Regardless of the methodological approach chosen, it is essential to justify the choice and outline its potential limitations, in accordance with ISO standards (de Alvarenga et al., 2012; ISO, 2006a, 2006b).

4. Conclusion

In this research an attempt to harmonize soil C estimation tools in LCA of agricultural systems was carried out together with providing recommendations for LCA practitioners and scientists. Increasing net soil C storage by even a small percentage, represents substantial C accumulation potential and mitigation of GHG emissions, reducing climate impacts. It was observed that a high level of accuracy corresponded to a low level of applicability and vice versa. Thus, the choice of the methodology in relation to the LCA objectives is particularly critical to enable the best possible LCA assessments for the climate impact indicator.

Following the analysis of the available literature, a series of preliminary recommendations were proposed:

- As a general recommendation for all the GHG assessments for agricultural systems, the choice of LCA estimation tools for the individual impact categories should be based on the LCA objectives and data availability. Specifically, for estimating the GHGs the soil carbon changes are extremely important;
- It is crucial to be aware of the shift from one soil carbon equilibrium to the other and the potential decisive effect of the initial soil carbon content and the assessment period.
- More complex methods are available, but they have greater data requirements and additional training or collaboration with modelling experts is required. At the other end of the complexity spectrum, the IPCC Tier 1 methodology has been employed in most of the assessments analysed here. Thus, for soil carbon there are only a few IPCC Tier 2 or basic process model solutions which combine the need for applicability with the need of accuracy;
- Independently of the estimation tool used, estimation tool limitations should be discussed in the LCA of agricultural systems.

Two critical challenges in including soil carbon estimates in climate impact assessments are establishing a baseline (initial soil carbon content) and determining an appropriate time perspective. The influence of past practices and crop types on the initial status of soil carbon will affect the results of the soil C accounting estimation tools. This problem may not exist when conducting a site-specific assessment for a single land unit or farm, as historical data may be available to make accurate estimates. However, when performing a site-dependent or site-generic large-scale assessment, such as evaluating soil carbon content at the national level, issues of overestimation or underestimation can arise due to the lack of historical data. This should be taken into account for future development of LCA methodology on soil carbon changes in agricultural systems. In summary, this study provides a solid framework for harmonizing soil carbon estimation methodologies within the agricultural and livestock LCA, improving current practices through the identification of methodological strengths and limitations. This research identified methodological gaps, especially those related to time horizons and initial carbon content in soil. Further, it provides valuable insights for researchers, practitioners and policy-makers involved in the assessment and mitigation of climate impacts in different agricultural systems. Our recommendations can enhance decision-making capacity, thereby supporting the sustainable transformation of agricultural systems towards climate neutrality.

CRediT authorship contribution statement

Simone Pelaracci: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Pietro Goglio:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Simon Moakes:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marie Trydeman Knudsen:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Klara Van Mierlo:** Methodology, Investigation, Formal analysis, Data curation. **Nina Adams:** Methodology, Investigation, Formal analysis, Data curation. **Fossey Maxime:** Methodology, Investigation, Formal analysis, Data curation. **Alberto Maresca:** Writing – review & editing, Methodology. **Manuel Romero-Huelva:** Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Muhammad Ahmed Waqas:** Methodology, Investigation, Formal analysis, Data curation. **Laurence G. Smith:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Frank Willem Oudshoorn:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Thomas Nemecek:** Writing – review & editing, Supervision. **Camillo de Camillis:** Writing – review & editing, Supervision. **Giampiero Grossi:** Writing – review & editing, Supervision. **Ward Smith:** Writing – review & editing, Supervision.

Funding sources

This research has been developed within the PATHWAYS project, funded by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 101000395.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Simone Pelaracci, Pietro Goglio, Simon Moakes, Marie Trydeman Knudsen, Klara Van Mierlo, Nina Adams, Fossey Maxime, Alberto Maresca, Manuel Romero-Huelva, Muhammad Ahmed Waqas, Laurence G. Smith, Frank Willem Oudshoorn, Thomas Nemecek report financial support was provided by H2020 Food Security Sustainable Agriculture and Forestry Marine Maritime and Inland Water Research and the Bioeconomy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104361.

Data availability

Data will be made available on request.

References

Aalde, H., Gonzalez, Gytarsky, Krug, 2006. Vol 4: agriculture, forestry, and other land use, Chap. 2: generic methodologies applicable to multiple land-use. In: IPCC Guidelines for National Greenhouse Gas Inventories.

Allen, D., Pringle, M., Page, K., Dalal, R., 2010. A review of sampling designs for the measurement of soil organic carbon in Australian grazing lands. Rangeland J. 32, 227–246.

Andrén, O., Kätterer, T., 1997. ICBM: the introductory carbon balance model for exploration of soil carbon balances. Ecol. Appl. 7, 1226–1236. https://doi.org/10.1890/1051-0761(1997)007[1226:ITICBM]2.0.CO;2.

Arrouays, D., Marchant, B., Saby, N., Meersmans, J., Orton, T., Martin, M.P., Bellamy, P., Lark, R., Kibblewhite, M., 2012. Generic issues on broad-scale soil monitoring schemes: a review. Pedosphere 22, 456–469.

Bai, Y., Cotrufo, M.F., 2022. Grassland soil carbon sequestration: current understanding, challenges, and solutions. Science 377, 603–608. https://doi.org/10.1126/science.abo2380.

Bardgett, R.D., Bullock, J.M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M., Durigan, G., Fry, L., Johnson, D., Lavallee, J.M., Le Provost, G., Luo, S., Png, K., Sankaran, M., Hou, X., Zhou, H., Ma, L., Ren, W., Li, X., Ding, Y., Li, Y., Shi, H., 2021. Combatting global grassland degradation. Nat. Rev. Earth Environ. 2, 720–735. https://doi.org/10.1038/s43017-021-00207-2.

Batjes, N.H., 2014. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 65, 10–21. https://doi.org/10.1111/ejss.12114_2.

Brady, N., Weil, R., 2002. The Nature and Properties of Soils, 13th ed. Prentice Hall, Upper Saddle River, New Jersey, USA.

Brandão, M., Levasseur, A., Kirschbaum, M.U.F., Weidema, B.P., Cowie, A.L., Jørgensen, S.V., Hauschild, M.Z., Pennington, D.W., Chomkhamsri, K., 2013. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. Int. J. Life Cycle Assess. 18, 230–240. https://doi.org/10.1007/s11367-012-0451-6.

Brandão, M., Kirschbaum, M.U.F., Cowie, A.L., Hjuler, S.V., 2019. Quantifying the climate change effects of bioenergy systems: comparison of 15 impact assessment methods. GCB Bioenergy 11, 727–743. https://doi.org/10.1111/gcbb.12593.

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Trusler, J.P.M., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11, 1062–1176. https://doi.org/10.1039/C7EE02342A.

Cabot, M.I., Lado, J., Clemente, G., Sanjuán, N., 2022. Towards harmonised and regionalised life cycle assessment of fruits: a review on citrus fruit. Sustain. Prod. Consump. 33, 567–585.

Camargo, G.G.T., Ryan, M.R., Richard, T.L., 2013. Energy use and greenhouse gas emissions from crop production using the farm energy analysis tool. BioScience 63, 263–273. https://doi.org/10.1525/bio.2013.63.4.6.

Canals, L., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., Edwards-Jones, G., Hounsome, B., 2008. Life Cycle Assessment (LCA) of Domestic Vs. Imported Vegetables. Case Studies on Broccoli, Salad Crops and Green Beans.

Ciais, P., et al., 2013. Carbon and other biogeochemical cycles. In: Stocker, T.F., et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013. Cambridge Univ. Press, pp. 465–570.

Costa, M.P., Chadwick, D., Saget, S., Rees, R.M., Williams, M., Styles, D., 2020. Representing crop rotations in life cycle assessment: a review of legume LCA studies. Int. J. Life Cycle Assess. 25, 1942–1956. https://doi.org/10.1007/s11367-020-01812-x.

Dale, B.E., Kim, S., 2014. Can the predictions of consequential life cycle assessment be tested in the real world? Comment on "using attributional life cycle assessment to estimate climate-change mitigation.". J. Ind. Ecol. 18, 466–467. https://doi.org/10.1111/jiec.12151.

de Alvarenga, R.A.F., da Silva Júnior, V.P., Soares, S.R., 2012. Comparison of the ecological footprint and a life cycle impact assessment method for a case study on Brazilian broiler feed production. J. Clean. Prod. 28, 25–32. https://doi.org/10.1016/j.jclepro.2011.06.023.

Del Grosso, S.J., Smith, W., Kraus, D., Massad, R.S., Vogeler, I., Fuchs, K., 2020. Approaches and concepts of modelling denitrification: increased process understanding using observational data can reduce uncertainties. Curr. Opin. Environ. Sustain. 47, 37–45. https://doi.org/10.1016/j.cosust.2020.07.003.

Dlamini, P., Chivenge, P., Chaplot, V., 2016. Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: a meta-analysis shows. Agric. Ecosyst. Environ. 221, 258–269. https://doi.org/10.1016/j.agee.2016.01.026.

Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., Emde, D., Seitz, D., Chenu, C., 2024. Carbon sequestration in soils and climate change mitigation—definitions and pitfalls. Glob. Chang. Biol. 30, e16983. https://doi.org/10.1111/gcb.16983.

Ehrhardt, F., Soussana, J., Bellocchi, G., Grace, P., McAuliffe, R., Recous, S., Sándor, R., Smith, P., Snow, V., de Antoni Migliorati, M., 2018. Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N2O emissions. Glob. Chang. Biol. 24, e603–e616.

Eze, S., Palmer, S.M., Chapman, P.J., 2018. Soil organic carbon stock in grasslands: effects of inorganic fertilizers, liming and grazing in different climate settings. J. Environ. Manag. 223, 74–84. https://doi.org/10.1016/j.jenvman.2018.06.013.

FAO, 2016a. Environmental Performance of Pig Supply Chains: Guidelines for Assessment (Livestock Environmental 251 Assessment and Performance Partnership). Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2016b. Environmental Performance of Animal Feeds Supply Chains: Guidelines for Assessment. Livestock Environmental Assessment and Performance (LEAP) Partnership. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2016c. Greenhouse Gas Emissions and Fossil Energy Use from Small Ruminant Supply Chains: Guidelines for Assessment. Livestock Environmental Assessment and Performance (LEAP) Partnership. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2016d. Greenhouse Gas Emissions and Fossil Energy Use from Poultry Supply Chains: Guidelines for Assessment. Livestock Environmental Assessment and Performance (LEAP) Partnership. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2016e. Environmental Performance of Large Ruminant Supply Chains: Guidelines for Assessment. Livestock Environmental Assessment and Performance (LEAP) Partnership. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2018. Measuring and Modelling Soil Carbon Stocks and Stock Changes in Livestock Production Systems – Guidelines for Assessment (Draft for Public Review). Livestock Environmental Assessment and Performance (LEAP) Partnership. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2019. Measuring and Modelling Soil Carbon Stocks and Stock Changes in Livestock Production Systems: Guidelines for Assessment (Version 1). Livestock Environmental Assessment and Performance (LEAP) Partnership. FAO, Rome, p. 170 (Licence: CC BY-NC-SA 3.0 IGO).

FAO, 2020. Livestock Environmental Assessment and Performance (LEAP) Partnership | Food and Agriculture Organization of the United Nations [WWW Document]. Food and Agriculture Organisation, Rome. URL. http://www.fao.org/partnerships/leap/en/ (accessed 5.11.20).

Fein, E.C., Gilmour, J., Machin, T., 2022. Statistics for Research Students.

FIL-IDF, 2022. C-Sequ. Life Cycle Assessment Guidelines for Calculating Carbon Sequestration in Cattle Production Systems. Fédération Internationale du Lait-International Dairy Federation, Brussels.

Gabrielle, B., Gagnaire, N., 2008. Life-cycle assessment of straw use in bio-ethanol production: a case study based on biophysical modelling. Biomass Bioenergy 32, 431–441. https://doi.org/10.1016/j.biombioe.2007.10.017.

Gan, Y., Liang, C., Chai, Q., Lemke, R.L., Campbell, C.A., Zentner, R.P., 2014. Improving farming practices reduces the carbon footprint of spring wheat production. Nat. Commun. 5, 5012. https://doi.org/10.1038/ncomms6012.

Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. Science 361, eaam5324. https://doi.org/10.1126/science.aam5324.

Goglio, P., Grant, B.B., Smith, W.N., Desjardins, R.L., Worth, D.E., Zentner, R., Malhi, S. S., 2014. Impact of management strategies on the global warming potential at the cropping system level. Sci. Total Environ. 490, 921–933. https://doi.org/10.1016/j.scitotenv.2014.05.070.

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., McConkey, B.G., Campbell, C.A., Nemecek, T., 2015. Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review. J. Clean. Prod. 104, 23–39. https://doi.org/10.1016/j.jclepro.2015.05.040.

Goglio, P., Brankatschk, G., Knudsen, M.T., Williams, A.G., Nemecek, T., 2017. Addressing crop interactions within cropping systems in LCA. Int. J. Life Cycle Assess. 1–9. https://doi.org/10.1007/s11367-017-1393-9.

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., Gao, X., Hanis, K., Tenuta, M., Campbell, C.A., McConkey, B.G., Nemecek, T., Burgess, P.J., Williams, A.G., 2018a. A comparison of methods to quantify greenhouse gas emissions of cropping systems in LCA. J. Clean. Prod. 172. https://doi.org/10.1016/j.jclepro.2017.03.133.

Goglio, Pietro, Smith, W.N., Worth, D.E., Grant, B.B., Desjardins, R.L., Chen, W., Tenuta, M., McConkey, B.G., Williams, A., Burgess, P., 2018b. Development of Crop.LCA, an adaptable screening life cycle assessment tool for agricultural systems: a Canadian scenario assessment. J. Clean. Prod. 172, 3770–3780. https://doi.org/10.1016/j.jclepro.2017.06.175.

Goglio, P., Williams, A., Balta-Ozkan, N., Harris, N.R.P., Williamson, P., Huisingh, D., Zhang, Z., Tavoni, M., 2019. Advances and challenges of life cycle assessment (LCA) of greenhouse gas removal technologies to fight climate changes. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.118896, 118896.

Goglio, P., Knudsen, M.T., Van Mierlo, K., Röhrig, N., Fossey, M., Maresca, A., Hashemi, F., Waqas, M.A., Yngvesson, J., Nassy, G., Broekema, R., Moakes, S., Pfeifer, C., Borek, R., Yanez-Ruiz, D., Cascante, M.Q., Syp, A., Zylowsky, T., Romero-Huelva, M., Smith, L.G., 2023. Defining common criteria for harmonizing life cycle assessments of livestock systems. Clean. Prod. Lett. 4, 100035. https://doi.org/10.1016/j.clpl.2023.100035.

Goglio, P., Moakes, S., Knudsen, M.T., Mierlo, K.V., Adams, N., Maxime, F., Maresca, A., Romero-Huelva, M., Waqas, M.A., Smith, L.G., Grossi, G., Smith, W., Camillis, C.D., Nemecek, T., Tei, F., Oudshoorn, F.W., 2024. Harmonizing methods to account for soil nitrous oxide emissions in life cycle assessment of agricultural systems. Agric. Syst. 219, 104015. https://doi.org/10.1016/j.agsy.2024.104015.

Grossi, G., Goglio, P., Vitali, A., Williams, A.G., 2019. Livestock and climate change: impact of livestock on climate and mitigation strategies. Anim. Front. 9, 69–76. https://doi.org/10.1093/af/vfy034.

Halberg, N., Hermansen, J.E., Kristensen, I.S., Eriksen, J., Tvedegaard, N., Petersen, B.M., 2010. Impact of organic pig production systems on CO2 emission, C sequestration and nitrate pollution. Agron. Sustain. Dev. 30, 721–731. https://doi.org/10.1051/agro/2010006.

He, W., Grant, B.B., Jing, Q., Lemke, R., St. Luce, M., Jiang, R., Qian, B., Campbell, C.A., Vander Zaag, A., Zou, G., Smith, W.N., 2021. Measuring and modeling soil carbon sequestration under diverse cropping systems in the semiarid prairies of western Canada. J. Clean. Prod. 328, 129614. https://doi.org/10.1016/j.jclepro.2021.129614.

Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Wirsenius, S., Hristov, A.N., Gerber, P., Gill, M., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Chang. 6, 452–461.

Hillier, J., Whittaker, C., Dailey, G., Aylott, M., Casella, E., Richter, G.M., Riche, A., Murphy, R., Taylor, G., Smith, P., 2009. Greenhouse gas emissions from four bioenergy crops in England and Wales: integrating spatial estimates of yield and soil carbon balance in life cycle analyses. GCB Bioenergy 1, 267–281. https://doi.org/10.1111/j.1757-1707.2009.01021.x.

Hörtenhuber, S., Lindenthal, T., Amon, B., Markut, T., Kirner, L., Zollitsch, W., 2010. Greenhouse gas emissions from selected Austrian dairy production systems—model calculations considering the effects of land use change. Renew. Agric. Food Syst. 25, 316–329. https://doi.org/10.1017/S1742170510000025.

IPCC, 2022. Climate change 2022: Mitigation of climate change. In: WGIII Mitigation of Climate Change Climate Change 2022 Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Interngovernmental Panel for Climate Change, Geneva, Switzerland.

ISO, 2006a. SS-EN ISO 14044 Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva.

ISO, 2006b. SS-EN ISO 14040 Environmental Management- Life Cycle Assessment, Principles and Framework. International Organization for Standardization, Geneva.

ITPS, F, 2015. Status of the world's soil resources (SWSR)—Main report. In: Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, p. 650.

Jensen, A., Mogensen, L., van der Werf, H.M.G., Xie, Y., Kristensen, H.L., Knudsen, M.T., 2024. Environmental impacts and potential mitigation options for organic open-field vegetable production in Denmark assessed through life cycle assessment. Sustain. Prod. Consumpt. 46, 132–145. https://doi.org/10.1016/j.spc.2024.02.008.

Jérôme, E., Beckers, Y., Bodson, B., Heinesch, B., Moureaux, C., Aubinet, M., 2014. Impact of grazing on carbon dioxide exchanges in an intensively managed Belgian grassland. Agric. Ecosyst. Environ. 194, 7–16.

Jiang, R., Jayasundara, S., Grant, B.B., Smith, W.N., Qian, B., Gillespie, A., Wagner-Riddle, C., 2023. Impacts of land use conversions on soil organic carbon in a warming-induced agricultural frontier in northern Ontario, Canada under historical and future climate. J. Clean. Prod. 404, 136902. https://doi.org/10.1016/j.jclepro.2023.136902.

Jourdaine, M., Loubet, P., Trebucq, S., Sonnemann, G., 2020. A detailed quantitative comparison of the life cycle assessment of bottled wines using an original harmonization procedure. J. Clean. Prod. 250, 119472. https://doi.org/10.1016/j.jclepro.2019.119472.

Kane, D., Solutions, L.L.C., 2015. Carbon sequestration potential on agricultural lands: a review of current science and available practices. In: National Sustainable Agriculture Coalition Breakthrough Strategies and Solutions, LLC, pp. 1–35.

Klumpp, K., Bloor, J.M.G., Ambus, P., Soussana, J.-F., 2010. Effects of clover density on N2O emissions and plant-soil N transfers in a fertilised upland pasture. Plant Soil 343, 97–107. https://doi.org/10.1007/s11104-010-0526-8.

Knudsen, M.T., Meyer-Aurich, A., Olesen, J.E., Chirinda, N., Hermansen, J.E., 2014. Carbon footprints of crops from organic and conventional arable crop rotations – using a life cycle assessment approach. J. Clean. Prod. 64, 609–618. https://doi.org/10.1016/j.jclepro.2013.07.009.

Knudsen, M.T., Dorca-Preda, T., Djomo, S.N., Peña, N., Padel, S., Smith, L.G., Zollitsch, W., Hörtenhuber, S., Hermansen, J.E., 2019. The importance of including soil carbon changes, ecotoxicity and biodiversity impacts in environmental life cycle assessments of organic and conventional milk in Western Europe. J. Clean. Prod. 215, 433–443. https://doi.org/10.1016/j.jclepro.2018.12.273.

Koerber, G.R., Edwards-Jones, G., Hill, P.W., Canals, L.M., Nyeko, P., York, E.H., Jones, D.L., 2009. Geographical variation in carbon dioxide fluxes from soils in agro-ecosystems and its implications for life-cycle assessment. J. Appl. Ecol. 46, 306–314. https://doi.org/10.1111/j.1365-2664.2009.01622.x.

Lal, R., Stewart, B.A. (Eds.), 2018. Soil and Climate, 1st ed. CRC Press, Boca Raton. https://doi.org/10.1201/b21225.

Lal, R., Monger, C., Nave, L., Smith, P., 2021. The role of soil in regulation of climate. Philos. Trans. R. Soc. B 376, 20210084. https://doi.org/10.1098/rstb.2021.0084.

Le Quéré, C., Andrew, R.M., Canadell, J.G., Sitch, S., Korsbakken, J.I., Peters, G.P., Manning, A.C., Boden, T.A., Tans, P.P., Houghton, R.A., Keeling, R.F., Alin, S., Andrews, O.D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L.P., Ciais, P., Currie, K., Delire, C., Doney, S.C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A.K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J.R., Metzl, N., Millero, F., Monteiro, P.M.S., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S., O'Brien, K., Olsen, A., Omar, A.M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B.D., Sutton, A.J., Takahashi, T., Tian, H., Tilbrook, B., van der Laan-Luijkx, I.T., van der Werf, G.R., Viovy, N., Walker, A.P., Wiltshire, A.J., Zaehle, S., 2016. Global carbon budget 2016. Earth Syst. Sci. Data 8, 605–649. https://doi.org/10.5194/essd-8-605-2016.

Lefebvre, D., Williams, A., Kirk, G.J.D., Meersmans, J., Sohi, S., Goglio, P., Smith, P., 2021. An anticipatory life cycle assessment of the use of biochar from sugarcane residues as a greenhouse gas removal technology. J. Clean. Prod. 312, 127764. https://doi.org/10.1016/j.jclepro.2021.127764.

Li, C., Narayanan, V., Harriss, R.C., 1996. Model estimates of nitrous oxide emissions from agricultural lands in the United States. Glob. Biogeochem. Cycles 10, 297–306. https://doi.org/10.1029/96GB00470.

Loubet, B., Laville, P., Lehuger, S., Larmanou, E., Fléchard, C., Mascher, N., Genermont, S., Roche, R., Ferrara, R.M., Stella, P., Personne, E., Durand, B., Decuq, C., Flura, D., Masson, S., Fanucci, O., Rampon, J.-N., Siemens, J., Kindler, R., Gabrielle, B., Schrumpf, M., Cellier, P., 2011. Carbon, nitrogen and greenhouse gases budgets over a four years crop rotation in northern France. Plant Soil 343, 109–137. https://doi.org/10.1007/s11104-011-0751-9.

MacWilliam, S., Wismer, M., Kulshreshtha, S., 2014. Life cycle and economic assessment of Western Canadian pulse systems: the inclusion of pulses in crop rotations. Agric. Syst. 123, 43–53. https://doi.org/10.1016/j.agsy.2013.08.009.

Chapter 6: Grassland. In: McConkey, B., Ogle, S.M., Chirinda, N., Kishimoto-Mo, A.W., Baldock, J., Trunov, A., Alsaker, C., Lehmann, J., Woolf, D. (Eds.), 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, Intergovernmental Panel for Climate Change, Geneva, Switzerland.

McSherry, M.E., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon: a global review. Glob. Chang. Biol. 19, 1347–1357.

Morais, T.G., Jongen, M., Tufik, C., Rodrigues, N.R., Gama, I., Serrano, J., Gonçalves, M.C., Mano, R., Domingos, T., Teixeira, R.F.M., 2023. Satellite-based estimation of soil organic carbon in Portuguese grasslands. Front. Environ. Sci. 11. https://doi.org/10.3389/fenvs.2023.1240106.

Morris, J., Brown, S., Cotton, M., Matthews, H.S., 2017. Life-cycle assessment harmonization and soil science ranking results on food-waste management methods. Environ. Sci. Technol. 51, 5360–5367. https://doi.org/10.1021/acs.est.6b06115.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Glob. Food Sec. 14, 1–8. https://doi.org/10.1016/j.gfs.2017.01.001.

Nguyen, T.H., Field, J.L., Kwon, H., Hawkins, T.R., Paustian, K., Wang, M.Q., 2022. A multi-product landscape life-cycle assessment approach for evaluating local climate mitigation potential. J. Clean. Prod. 354, 131691. https://doi.org/10.1016/j.jclepro.2022.131691.

Oates, L.G., Jackson, R.D., 2014. Livestock management strategy affects net ecosystem carbon balance of subhumid pasture. Rangel. Ecol. Manag. 67, 19–29.

Oberholzer, H.R., Leifeld, J., Mayer, J., 2014. Changes in soil carbon and crop yield over 60 years in the Zurich organic fertilization experiment, following land-use change from grassland to cropland. J. Plant Nutr. Soil Sci. 177, 696–704. https://doi.org/10.1002/jpln.201300385.

Ogle, S., Kurz, W.A., Green, C., Brandon, A., Baldock, J., Domke, J., Herold, M., Bernoux, M., Chirinda, N., De Ligt, R., Federici, S., Garcia, E., Grassi, G., Gschwantner, T., Hirata, Y., Houghton, R., House, J.J., Ishizuka, S., Jonckheere, I., Krisnawati, H., Lehtonen, A., Kinyanjui, M.J., McConkey, B., Naesset, E., Niinistö, S. M., Ometto, J.P., Panichelli, L., Paul, T., Peterson, H., Reddy, S., Regina, K., Rocha, M., Rock, J., Sanz-Sanchez, M., Sanquetta, S., Sato, S., Somogyi, Z., Trunov, A., Vazquez-Amabile, G., Vitullo, M., Wang, C., Waterworth, R.M., Collet, M., Harmon, M., Lehmann, J., Shaw, C.H., Shirato, Y., Wolf, D., 2019a. Chapter 2: Generic methodologies, applicable to multiple land-use categories. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse gas Inventories. IPCC, Intergovernmental Panel for Climate Change, Geneva.

Ogle, S., Wakelin, S.J., Buendia, L., McConckey, B., Baldock, J., Akiyama, H., Kishimoto-Mo, A.M., Chirinda, N., Bernoux, M., Bhattacharya, S., Chuersuwan, N., Goheer, M. A.R., Hergoualc'h, K., Ishizuka, S., Lasco, R.D., Pan, X., Pathak, H., Regina, K., Sato, A., Vazquez-Amabile, G., Wang, C., Zheng, X., Alsaker, C., Cardinael, R., Corre, M.D., Gurung, R., Mori, A., Lehmann, J., Rossi, S., Van Straaten, O., Veldkamp, E., Woolf, D., Yagi, K., Yan, X., 2019b. Chapter 5: Cropland. In: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse gas Inventories. IPCC International Panel on Climate Change, Geneva.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57. https://doi.org/10.1038/nature17174.

Pelaracci, S., 2024. General and Specific Criteria for Evaluation of Methods for Accounting of C Exchanges between Soil and Atmosphere in LCA of Crop Livestock-System. https://doi.org/10.5281/zenodo.10683622.

Pelaracci, S., Rocchi, L., Romagnoli, F., Boggia, A., Paolotti, L., 2022. Agricultural co-product management: an LCA perspective on the use of safflower oilcake from bio-oil production in Umbria region, Italy. Environ. Clim. Technol. 26, 25–35. https://doi.org/10.2478/rtuect-2022-0003.

Pelletier, Thiagarajan, Durnin-Vermette, Liang, Choo, Cerkowniak, Elkhoury, MacDonald, Smith, Vanden Bygaart, 2024. Bayesian Calibration of the Ipcc Tier-2 Steady-State Organic Carbon Model for Canadian Croplands Using Long-Term Experimental Data. https://doi.org/10.2139/ssrn.4877052.

Perlman, J., Hijmans, R.J., Horwath, W.R., 2013. Modelling agricultural nitrous oxide emissions for large regions. Environ. Model Softw. 48, 183–192. https://doi.org/10.1016/j.envsoft.2013.07.002.

Petersen, B.M., Knudsen, M.T., Hermansen, J.E., Halberg, N., 2013. An approach to include soil carbon changes in life cycle assessments. J. Clean. Prod. 52, 217–224. https://doi.org/10.1016/j.jclepro.2013.03.007.

Planton, S., 2013. Annex III: glossary. Climate Change 1447–1465.

Plevin, R.J., 2017. Assessing the climate effects of biofuels using integrated assessment models, part I: methodological considerations. J. Ind. Ecol. 21, 1478–1487. https://doi.org/10.1111/jiec.12507.

Potting, J., Hauschild, M.Z., 2006. Spatial differentiation in life cycle impact assessment: a decade of method development to increase the environmental realism of LCIA. Int. J. Life Cycle Assess. 11, 11–13. https://doi.org/10.1065/lca2006.04.005.

Pouladi, N., Gholizadeh, A., Khosravi, V., Borůvka, L., 2023. Digital mapping of soil organic carbon using remote sensing data: a systematic review. CATENA 232, 107409. https://doi.org/10.1016/j.catena.2023.107409.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Chang. 4, 678–683. https://doi.org/10.1038/nclimate2292.

Rodrigues, C.I.D., Brito, L.M., Nunes, L.J.R., 2023. Soil carbon sequestration in the Context of climate change mitigation: a review. Soil Syst. 7. https://doi.org/10.3390/soilsystems7030064.

Röös, E., Sundberg, C., Hansson, P.-A., 2010. Uncertainties in the carbon footprint of food products: a case study on table potatoes. Int. J. Life Cycle Assess. 15, 478–488.

Rotz, C.A., 2018. Modeling greenhouse gas emissions from dairy farms. J. Dairy Sci. 101, 6675–6690. https://doi.org/10.3168/jds.2017-13272.

Segura-Salazar, J., Lima, F.M., Tavares, L.M., 2019. Life cycle assessment in the minerals industry: current practice, harmonization efforts, and potential improvement through the integration with process simulation. J. Clean. Prod. 232, 174–192. https://doi.org/10.1016/j.jclepro.2019.05.318.

Senapati, N., Jansson, P.-E., Smith, P., Chabbi, A., 2016. Modelling heat, water and carbon fluxes in mown grassland under multi-objective and multi-criteria constraints. Environ. Model Softw. 80, 201–224.

Siegert, M.-W., Lehmann, A., Emara, Y., Finkbeiner, M., 2019. Harmonized rules for future LCAs on pharmaceutical products and processes. Int. J. Life Cycle Assess. 24, 1040–1057. https://doi.org/10.1007/s11367-018-1549-2.

Smith, W.N., Grant, B.B., Campbell, C.A., McConkey, B.G., Desjardins, R.L., Kröbel, R., Malhi, S.S., 2012. Crop residue removal effects on soil carbon: measured and inter-model comparisons. Agric. Ecosyst. Environ. 161, 27–38. https://doi.org/10.1016/j.agee.2012.07.024.

Soussana, J.-F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal 4, 334–350.

Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., Six, J., 2007. Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86, 19–31. https://doi.org/10.1007/s10533-007-9140-0.

Stöckle, C., Higgins, S., Kemanian, A., Nelson, R., Huggins, D., Marcos, J., Collins, H., 2012a. Carbon storage and nitrous oxide emissions of cropping systems in eastern Washington: a simulation study. J. Soil Water Conserv. 67, 365. https://doi.org/10.2489/jswc.67.5.365.

Stöckle, C., Higgins, S., Kemanian, A., Nelson, R., Huggins, D., Marcos, J., Collins, H., 2012b. Carbon storage and nitrous oxide emissions of cropping systems in eastern Washington: a simulation study. J. Soil Water Conserv. 67, 365–377. https://doi.org/10.2489/jswc.67.5.365.

Sykes, A.J., Topp, C.F.E., Rees, R.M., 2019. Understanding uncertainty in the carbon footprint of beef production. J. Clean. Prod. 234, 423–435. https://doi.org/10.1016/j.jclepro.2019.06.171.

Testa, F., Tessitore, S., Buttol, P., Iraldo, F., Cortesi, S., 2022. How to overcome barriers limiting LCA adoption? The role of a collaborative and multi-stakeholder approach. Int. J. Life Cycle Assess. 27, 944–958.

Tuomi, M., Thum, T., Järvinen, H., Fronzek, S., Berg, B., Harmon, M., Trofymow, J.A., Sevanto, S., Liski, J., 2009. Leaf litter decomposition—estimates of global variability based on Yasso07 model. Ecol. Model. 220, 3362–3371. https://doi.org/10.1016/j.ecolmodel.2009.05.016.

Uzoma, K.C., Smith, W., Grant, B., Desjardins, R.L., Gao, X., Hanis, K., Tenuta, M., Goglio, P., Li, C., 2015. Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model. Agric. Ecosyst. Environ. 206, 71–83. https://doi.org/10.1016/j.agee.2015.03.014.

Van Zanten, H.H.E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P. J., Schader, C., De Boer, I.J.M., 2018. Defining a land boundary for sustainable livestock consumption. Glob. Chang. Biol. 24, 4185–4194. https://doi.org/10.1111/gcb.14321.

Wang, W., Fang, J., 2009. Soil respiration and human effects on global grasslands. Glob. Planet. Chang. 67, 20–28.

Wang, Y., Tao, F., Chen, Y., Yin, L., 2022. Interactive impacts of climate change and agricultural management on soil organic carbon sequestration potential of cropland in China over the coming decades. Sci. Total Environ. 817, 153018. https://doi.org/10.1016/j.scitotenv.2022.153018.

Wiedemann, S.G., Yan, M.-J., Henry, B.K., Murphy, C.M., 2016. Resource use and greenhouse gas emissions from three wool production regions in Australia. J. Clean. Prod. 122, 121–132. https://doi.org/10.1016/j.jclepro.2016.02.025.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., 2019. Food in the Anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. Lancet 393, 447–492.

Yang, Y., Tilman, D., Furey, G., Lehman, C., 2019. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nat. Commun. 10, 718. https://doi.org/10.1038/s41467-019-08636-w.

Zaher, U., Stöckle, C., Painter, K., Higgins, S., 2013. Life cycle assessment of the potential carbon credit from no- and reduced-tillage winter wheat-based cropping systems in Eastern Washington State. Agric. Syst. 122, 73–78. https://doi.org/10.1016/j.agsy.2013.08.004.

Zhang, Y., Liu, J., Wang, H., Lei, Q., Liu, H., Zhai, L., Ren, T., Zhang, J., 2018. Suitability of the DNDC model to simulate yield production and nitrogen uptake for maize and soybean intercropping in the North China plain. J. Integr. Agric. 17, 2790–2801. https://doi.org/10.1016/S2095-3119(18)61945-8.

Zhou, Y., Singh, J., Butnor, J.R., Coetsee, C., Boucher, P.B., Case, M.F., Hockridge, E.G., Davies, A.B., Staver, A.C., 2022. Limited increases in savanna carbon stocks over decades of fire suppression. Nature 603, 445–449. https://doi.org/10.1038/s41586-022-04438-1.