



## Framework for including national-level LULUC emissions and removals in the GWP of agricultural and forestry products in LCA

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### ARTICLE INFO

Handling Editor: Liu Yu

#### Keywords:

Life cycle assessment  
GHG emissions  
Soil carbon  
Forest land  
Cropland  
Global warming potential  
CO<sub>2</sub> removals

### ABSTRACT

Land use and land use change (LULUC) encompasses carbon stock changes in living biomass, dead organic matter, and soil organic carbon, causing LULUC-related greenhouse gas (GHG) emissions and removals reported as global warming potential (GWP<sub>LULUC</sub>). Regardless of the realised importance, accounting for LULUC in life cycle assessment (LCA) is challenging due to its complex nature and gaps in internationally recommended approaches. As a result, LULUC methods in LCA remain variable and often incomplete. Here, we aim to improve the inclusion of the national-level LULUC emissions and removals in LCA by providing a framework aligning with the National GHG Inventories. That is to enhance the practicality and use of open-access national-level LULUC data. Furthermore, we applied the framework to cropland and forest land, to demonstrate the effect of LULUC emissions and removals on the GWP of two typical Finnish agricultural and forestry products – oats and harvested softwood of Norway spruce. The developed framework provides a comprehensive consideration of carbon stocks, accounts for net carbon removals, and distinguishes mineral and organic soils. The case study results showed that consideration of LULUC increased the GWP of oats and mainly decreased the GWP of harvested softwood. The results highlight the importance of considering organic soils separately from mineral soils in areas high in organic soils, such as Finland. It is also important to consider net carbon removals of forest land, as they have potential to mitigate GWP. The framework includes LULUC emissions and removals based on national-level average data, but it can be specified by data regarding the share of organic soils and land use history. Including LULUC emissions and removals improves the completeness and accuracy of LCA. In the developed framework, the inclusion of LULUC is done by utilizing annually updating national-level GHG inventory data, to avoid partial or double counting and to enhance practicality. Special focus needs to be put on the share of organic soils on the production chain, which needs to be specified in areas high in organic soils such as Finland.

### 1. Introduction

Land use and land use change (LULUC) emissions constitute approximately 13–21 % of global greenhouse gas (GHG) emissions originating from anthropogenic sources (UNFCCC, 2024). These LULUC emissions hold a pivotal role in the global balance of anthropogenic GHG emissions and removals, influencing the dynamics of land as both carbon sink and source (De Rosa et al., 2017a; IPCC, 2021). LULUC is an important part of global warming potential (GWP) – also called climate impact, which is estimated with life cycle assessment (LCA; ISO, 2018). GWP is divided into three categories, one of which is GWP<sub>LULUC</sub>,

including human-driven LULUC emissions (CO<sub>2</sub>, CH<sub>4</sub>) and LULUC removals i.e., CO<sub>2</sub> removals from the atmosphere. The emissions and removals are related to carbon stock changes in living biomass (includes especially living tree biomass), dead organic matter (DOM; non-decomposed litter) and soil organic carbon (SOC) (ISO, 2018; IPCC, 2006a). GWP<sub>LULUC</sub> is driven by land use changes (LUC) and land management changes (LMC). LUC refers to human-driven change in land use (ISO, 2018) and is typically defined as a change from IPCC's land use category (IPCC, 2006a) to another – e.g., from forest land to cropland or from grassland to forest land. LMC refers to human-driven changes in land management, which cause land carbon stock changes when land

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<https://doi.org/10.1016/j.jclepro.2025.144999>

Received 23 September 2024; Received in revised form 16 January 2025; Accepted 9 February 2025

Available online 10 February 2025

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remains in the same land use category (IPCC, 2006a). Other categories of GWP include  $GWP_{\text{fossil}}$ , which refers to fossil GHG emissions, and  $GWP_{\text{biogenic}}$ , which includes biogenic GHG emissions not related to LULUC, but related to e.g., biogenic carbon in products (e.g., wood products) and  $CH_4$  emissions from livestock.

So far,  $GWP_{\text{LULUC}}$  has been excluded in many LCAs, and LULUC methodologies used in LCA have been variable (Goglio et al., 2015), although there are several guidance documents published advising to include LULUC emissions in LCA – e.g., European Commission's Environmental Footprint (EF) guidelines (2021), and PAS2050:2011 (BSI, 2011). Both LULUC emissions and removals shall be included in LCA following ISO 14067 (2018) standard. To date, LULUC emissions and/or removals have been included typically by utilizing IPCC Tier 1 (IPCC, 2006 a,b,c) and IPCC emissions factors for organic soils (2014). Also, PAS2050:2011 method (BSI, 2011) has been utilised in past research (for example in Leinonen et al., 2013; Usva et al., 2023). Those methods provide simplified factors to estimate LULUC emissions and/or removals on average global or national level, yet simple methods can potentially have limited accuracy in terms of pedo-climatic conditions and land management (Peter et al., 2016). Other methods include for example IPCC (2006b,c) Tier 3 methods that are, for example, simple carbon models, dynamic crop-climate-soil models and observations (Goglio et al., 2015). Those kinds of methods have been utilised in agricultural LCA studies, including the use of simple carbon models (e.g., Rööös et al., 2011; Korsæth et al., 2014; Joensuu et al., 2021; Saarinen et al., 2023; Lehtilä et al., 2024), and agroecological modelling (e.g., Adler et al., 2007; Sevenster et al., 2020). Yet, inclusion of LULUC emissions and removals in wide-scale LCA remains incomplete. That is because accounting for LULUC emissions and removals in LCA is challenging due to the complex and dynamic nature of carbon stock changes and gaps in internationally recommended approaches (Leinonen, 2022). Also, Tier 3 methods are often associated with complexity and limited practicality (Peter et al., 2016). The published guidance remains on a general level, which can limit implementation of LULUC emission and removal estimation.

LULUC inclusion methods need to be different for LCAs with different aims and scopes. The scope can be, for example, national or regional level, or specific field parcels or forest sites. In studies with national-level scope, the aim is typically to get LULUC emission and removal estimates representing the average land use history and management in the specific country. Typically, the methods for national-level LULUC emission and removal estimation are top-down (i.e. input-output) approaches. In general, LCA methods for LULUC need to be practical for LCA practitioners with varying expertise and representative of the whole production chain, including potentially hundreds or thousands of field parcels or forest sites, which are not always able to be traced. The potential difficulties in obtaining data limit the use of especially Tier 3 methods of LULUC in LCA. Nevertheless, IPCC Tier 1 estimates as such may not be representative enough for specific areas. Therefore, the LULUC methods used in LCA should be based on accessible data, which is representative of the production chain in terms of time and geography.

In this paper, we focus on LCA with national-level scope. Furthermore, we aim to develop a framework for LULUC emission and removal consideration in the LCA of agricultural and forestry products. We further aim to enhance practicality and possibility to utilise open-access, national-level average data from the National GHG Inventories to obtain secondary data for life cycle inventory (LCI). The framework is applied to Finnish cropland and forest land to provide national average  $GWP_{\text{LULUC}}$ , which is demonstrated on product level GWP for oats and harvested softwood production in Finland. Furthermore, the sensitivity of  $GWP_{\text{LULUC}}$  is assessed for different scenarios with varying input parameters to improve the robustness of the results.

## 2. Methods

In this section, principles of  $GWP_{\text{LULUC}}$  are described, the developed framework is introduced in detail, and the demonstration of the framework with case studies is described. The section is focused on cropland and forest land, yet the framework can be applied also to other land use categories. The case studies focus on Finnish agriculture and forestry, considering the country-specific soil and land use characteristics.

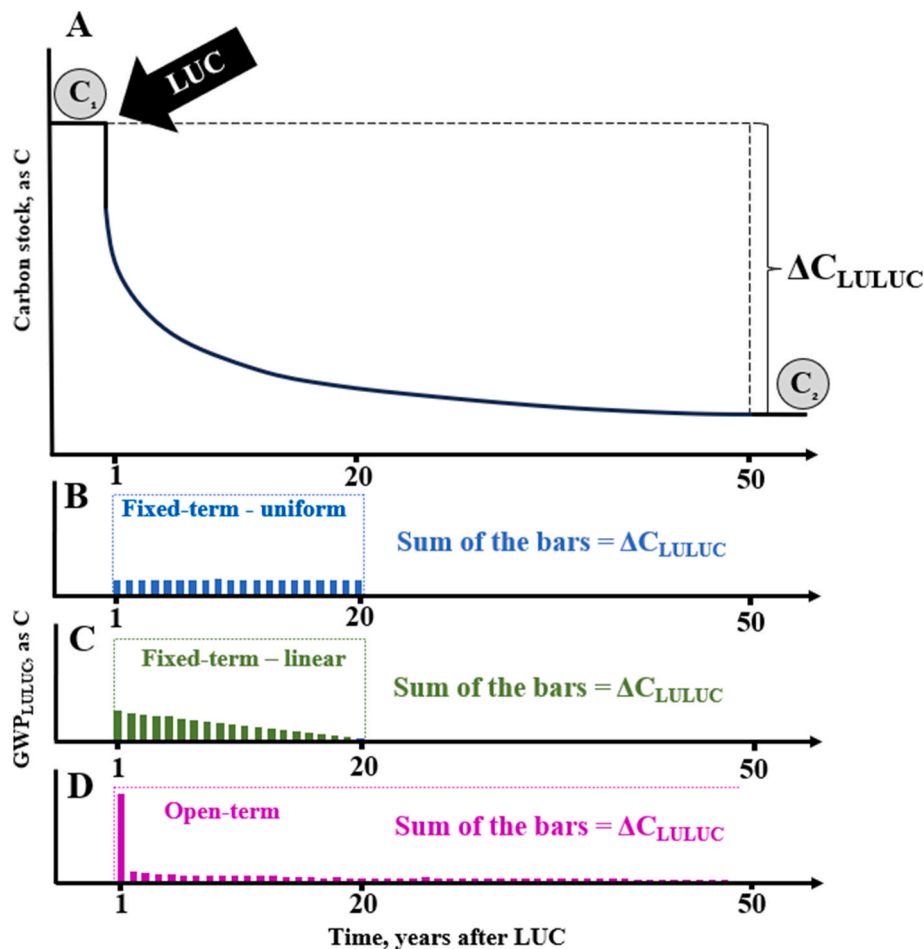
### 2.1. Principles of $GWP_{\text{LULUC}}$

Generally, all carbon stock changes – both positive and negative – within the system boundary shall be included (Leinonen, 2022). Typically, the system boundary of agricultural LCA extends often from cradle, i.e., raw material acquisition to the farm gate, factory gate, or end-of-life. In forest LCA, the system boundary usually extends from cradle to harvested product, factory gate, or end-of-life.

Carbon stock changes on land within the system boundary cause either net LULUC emissions or net LULUC removals, which are transitions between steady-state carbon stocks. Here, steady state refers to carbon stock equilibrium, which means no net changes in carbon stock. When a LUC or LMC occurs, the initial carbon stock ( $C_1$ ; carbon stock of the preceding land use or management) is not anymore in a steady state but undergoes changes until another steady-state carbon stock ( $C_2$ ; carbon stock of the current land use or management) is reached (Fig. 1). Difference between the two steady-state carbon stocks equals the total LULUC-related carbon stock change, i.e.  $\Delta C_{\text{LULUC}}$  ( $C_2 - C_1 = \Delta C_{\text{LULUC}}$ ). In principle, the original, historical steady-state carbon stock in all cases was natural vegetation, which has been converted to another land use. For example, in Finland, current forest land and cropland used to be natural forests before their human-driven conversion to land use for either agriculture or forestry. After the change from the natural vegetation to another land use, each change in land use or management shall be considered separately in LCA. For each assessment of  $GWP_{\text{LULUC}}$ , current land use is always compared with the preceding land use before the current land use. The same applies for land management, as the current land management is compared with the preceding land management before the current land management. In many cases, the original historical carbon stock and  $C_1$  are not equal, as the change from natural vegetation has often occurred a long time ago, and after that, every LUC or LMC before reaching  $C_1$  has already been accounted for.

Basically,  $\Delta C_{\text{LULUC}}$  shall be always allocated to products produced on the land area after LUC or LMC. Only the time of allocation varies, and is called as an *amortization period*, which is equivalent to responsibility window term used, for example, in IDF (2022) and Palosuo et al. (2025). Here, we define the amortization period as the time during which LULUC emissions or removals caused by a single LUC or LMC are allocated to products produced on the land area. Length of the amortization period varies depending on the LCA method used, but in all cases, the total  $\Delta C_{\text{LULUC}}$  remains the same (Fig. 1.).

We created a categorization for two different types of amortization periods, which we title as **fixed-term and open-term amortization periods**. Fixed-term amortization period means that total  $\Delta C_{\text{LULUC}}$  and consequent LULUC emissions or removals are allocated to products during a predefined time after an occurrence of LUC or LMC, although  $C_2$  is usually not yet reached (Fig. 1). The fixed-term amortization period is applied for example in IPCC (2006a, b) Tier 1 method. The typical length of fixed-term amortization period in agriculture is 20 years (BSI, 2011; IPCC, 2006a; IDF, 2022). Longer amortization periods have also been suggested, e.g., 100 years for Northern European conditions (Petersen et al., 2013). For forestry, the suggested length of the fixed-term amortization period is an average rotation length, i.e., time from stand establishment to final felling (ISO, 2018; BSI, 2011). Within the fixed-term amortization period, allocation of LULUC emissions and removals to products can be uniform meaning that an equal share of



**Fig. 1.** Example of consideration of a single land use change (LUC) in LCA: allocation of  $GWP_{LULUC}$  related to the  $\Delta C_{LULUC}$  (A) for products by using two different amortization periods – fixed-term (B, C) and open-term (D). For fixed-term amortization periods, two alternative allocation methods are presented – uniform allocation (C) and linear allocation (D). In all three examples,  $\Delta C_{LULUC}$  remains the same.  $C_1$  = carbon stock of the preceding land use before the current land use or management, an old steady state before the LUC; and  $C_2$  = carbon stock of the current land use, a new steady state after LUC. The same logic applies for LUC and land management changes (LMC). It applies also for LUC and LMC leading to net increase in carbon stocks. In that case, the curve (A) would be increasing, and the bars (B, C, D) would be negative indicating net carbon removals from the atmosphere and net negative  $GWP_{LULUC}$ .

LULUC emissions and removals is allocated to products on each year within the amortization period (Fig. 1; BSI, 2011). Another option is linear allocation, where share of LULUC emissions or removals is the highest in the first year after LUC or LMC and decreases linearly towards the end of the amortization period (Fig. 1; GHG protocol 2022).

Open-term amortization period refers to allocation of LULUC emissions and removals to products until steady state  $C_2$  is actually reached (Fig. 1). Thus, the length of the open-term amortization period is not pre-defined. In practice, open-term amortization period can be long – up to hundreds of years – especially under cool climate conditions. Open-term amortization period is typically applied in Tier 3 methods.

## 2.2. Developed framework

The framework presented in this section is based on the LCA framework for biogenic carbon by Leinonen (2022), which summarises current standards and guidelines. Following Leinonen (2022), the developed framework is mass-balanced, and within it, all sequential LUCs and LMCs are accounted for without partial or double counting. Here, we specify Leinonen's (2022) framework for LULUC emissions and removals to equation-level, to calculate  $GWP_{LULUC}$  per unit of a product (=functional unit). The framework applies a top-down (i.e., input-output) approach, and may be used to obtain secondary data for LCI. Here, we focus on national-level average type of land use and

management. Therefore, specific LUCs and LMCs for example at field, farm or forest site level are excluded from the framework.

$GWP_{LULUC}$  calculated with the framework includes  $CO_2$  and  $CH_4$  emissions and  $CO_2$  removals from the atmosphere, all related to LULUC. The framework aligns with IPCC's land use categorization (cropland/forest land/grassland/wetlands/settlements/other land use) and carbon stocks categorization (living biomass, DOM, SOC mineral soils and SOC organic soils) to enhance use of open-access and annually updating data from the National GHG Inventories provided by all Kyoto Protocol parties (UNFCCC, 2023). Furthermore, use of the National GHG Inventory data is chosen to improve the practicality of LCA.

In general, land use within this framework is divided into IPCC categories.

- i) land remaining in the same land use category, i.e., having no LUC in the past 20 years (=remaining land)
- ii) land converted from one land use category to another land use category within the past 20 years (=converted land).

For agricultural products, we include the following categories.

- i) cropland remaining cropland (CL remaining CL; land that has been cropland for at least 20 years)

ii) land converted to cropland (within the past 20 years; land converted to CL. The past land use categories include forest land, grassland, wetlands, settlements, and other land).

For forest products, we include the following categories.

- i) forest land remaining forest land (FL remaining FL; land that has been forest land for at least 20 years)
- ii) land converted to forest land (within the past 20 years; land converted to FL. The past land use categories include grassland, cropland, wetlands, settlements, and other land).

Note that conversions *from* cropland *to* another land use are excluded for agricultural products, and the conversions *from* forest land *to* another land use are excluded for forest products. This is because in those cases, the related GWP<sub>LULUC</sub> shall be allocated to the new land use, and not to the previous one.

The framework equations are presented in Eqs. (1)–(5). Specific equations separately for cropland and forest land are given in Supplementary material.

Firstly, GWP<sub>LULUC</sub> is a sum of CO<sub>2</sub> emissions and removals and CH<sub>4</sub> emissions, multiplied with an allocation factor (Eq. (1)):

$$GWP_{LULUC} = AF \times \left( \Delta C_{LULUC} \times \frac{44}{12} + CH_4 \times CF \right) \quad (1)$$

where:

GWP<sub>LULUC</sub> = LULUC-related global warming potential of a product, kg CO<sub>2</sub> eq/ha/yr; AF = allocation factor of product, dimensionless (Note: the factor is applied to allocate GWP<sub>LULUC</sub> to the studied product in case of several products are harvested from the same area (e.g., grain and straw));  $\Delta C_{LULUC}$  = LULUC-related carbon stock change, kg C/ha/yr;  $\frac{44}{12}$  = factor to convert carbon into CO<sub>2</sub>; CH<sub>4</sub> = methane emission from soil caused by LULUC, kg CH<sub>4</sub>/ha/yr; CF = characterization factor to convert CH<sub>4</sub> into CO<sub>2</sub> equivalents.

Secondly,  $\Delta C_{LULUC}$  is a weighted sum of carbon stock change on converted and remaining land (Eq. (2)):

$$\Delta C_{LULUC} = A_{conv} \times \Delta C_{conv} + A_{rem} \times \Delta C_{rem} \quad (2)$$

where:

$A_{conv}$  = share of land converted to a new land use category (within the past 20 years), dimensionless;  $\Delta C_{conv}$  = carbon stock change on land converted to a new land use category (within the past 20 years), kg C/ha/yr;  $A_{rem}$  = share of land remaining in the same land use category, dimensionless;  $\Delta C_{rem}$  = carbon stock change on land remaining in the same land use category, kg C/ha/yr.

Thirdly,  $\Delta C_{conv}$  and  $\Delta C_{rem}$  are calculated following similar equations (Eqs. (3) and (4)), but using different parameters for  $\Delta C_{LB}$ ,  $\Delta C_{DOM}$ , and  $\Delta C_{SOC}$ :

$$\Delta C_i = \Delta C_{LB,i} + \Delta C_{DOM,i} + \Delta C_{SOC,i} \quad (3)$$

$$\Delta C_{SOC,i} = A_{min} \times \Delta C_{SOC,min,i} + A_{org} \times \Delta C_{SOC,org,i} \quad (4)$$

where:

$\Delta C_{LB,i}$  = carbon stock change in living biomass on land area *i* (either converted or remaining), kg C/ha/yr;  $\Delta C_{DOM,i}$  = carbon stock change in dead organic matter on land area *i* (either converted or remaining), kg C/ha/yr;  $\Delta C_{SOC,i}$  = carbon stock change in soil organic carbon on land area *i* (either converted or remaining), kg C/ha/yr;  $A_{min}$  = share of mineral soil area, dimensionless (Note: can be further divided into  $A_{min,conv}$  and  $A_{min,rem}$ );  $A_{org}$  = share of organic soil area, dimensionless (Note: can be further divided into  $A_{org,conv}$  and  $A_{org,rem}$ );  $\Delta C_{SOC,min}$  = carbon stock change in soil organic carbon on mineral soils on land area *i* (either converted or remaining), kg C/ha/yr;  $\Delta C_{SOC,org,i}$  = carbon stock change in soil organic carbon on drained organic soils on land area *i* (either

converted or remaining), kg C/ha/yr.

Finally, CH<sub>4</sub> emissions from drained organic soils are calculated (Eq. (5)):

$$CH_4 = A_{org} \times CH_{4,org} \quad (5)$$

where:

CH<sub>4,org</sub> = methane emission from organic soil, kg CH<sub>4</sub>/ha/yr.

### 2.3. Oats and harvested softwood case studies

To demonstrate the use of developed framework, we applied it to average Finnish cropland and forest land. For agriculture, we focused only the GWP<sub>LULUC</sub> of Finnish cropland, as grassland has only a minor role in Finnish agriculture (Palosuo et al., 2015). The average GWP<sub>LULUC</sub> of Finnish cropland was integrated into the case study for oats (*Avena sativa* L.). Oats is a typical field crop in Finland, covering a total of 17 % of Finnish cropland, and cultivated in most of the regions in Finland (Luke, 2024). The average GWP<sub>LULUC</sub> of Finnish forest land was integrated in the case study for harvested softwood of Norwegian spruce (*Picea abies*), which is a typical tree species in Finland and covers around 30% of the total growing stock volume in Finnish forests (Luke, 2023).

Data used to calculate the average GWP<sub>LULUC</sub> of Finnish cropland and the average GWP<sub>LULUC</sub> of Finnish forest land were derived from the Common Reporting Format (CRF) table of Finland, an attachment of the National GHG Inventory Report (Statistics Finland, 2023). The CRF table data used represented years 2000–2021 and are available online at UNFCCC (2023). For GWP<sub>LULUC</sub> of cropland, data regarding CL remaining CL and land converted to CL were used. For GWP<sub>LULUC</sub> of forest land, data regarding FL remaining FL and land converted to FL were used. For land converted to CL (within the past 20 years), the past land use included all other land use categories (forest land, grassland, wetlands, settlements, and other land). Similarly, for land converted to FL (within the past 20 years), the past land use included all other land use categories (cropland, grassland, wetlands, settlements, and other land). Weighted averages of past land use categories for CL and FL in Finland in 2021 were used, based on data from CRF tables.

The methods to estimate carbon stock changes in the Finnish GHG Inventory are mainly Tier 3 methods based on Yasso (Tuomi et al., 2009) model and Tier 2 methods based on IPCC (2014) emission factors, which correspond with the definition of open-term amortization period (Table S1). Due to the Finnish GHG Inventory data, the amortization period type used was open-term in this case study, although generally, the developed framework can be used with both fixed-term and open-term amortization periods.

Shares of  $A_{conv}$ ,  $A_{rem}$ ,  $A_{min}$ , and  $A_{org}$  as well as per hectare carbon stock changes ( $\Delta C_{LULUC}$ ) in living biomass, DOM, and SOC were derived from CRF tables, and included in the cropland and forest land specific equations to calculate GWP<sub>LULUC</sub> for cropland and forest land in 2000–2021. The calculated GWP<sub>LULUC</sub> represented the average Finnish land use and management. Detailed information about deriving the values is presented in Supplementary material in Tables S2–S3, and the derived values are presented in Tables S4–S5.

Average GWP<sub>LULUC</sub> estimates based on the year 2021 data were included in the GWPs of oats and harvested softwood to i) demonstrate the effect of GWP<sub>LULUC</sub> inclusion and to ii) estimate the GHG emissions hotspots within the production chains. Overall, the GWPs of oats and harvested softwood were assessed following LCA principles (ISO, 2006a, b). For oats, the system boundary extended from cradle to farm gate, i.e. from raw material acquisition to grain yield drying at the farm. For harvested softwood, the system boundary extended from cradle to harvested product, and included plantation, silvicultural operations for stand management, and harvesting of softwood at the forest site. In accordance with the Finnish forestry recommendations (Tapio, 2023), harvesting usually involves precommercial thinning followed by first and second thinning, and final felling. The energy wood residues,

including treetops and branches, were assumed to be collected during precommercial thinning and final harvesting, while roots and stumps are left on the site. Functional units (FU) were defined as 1 kg of oats (grain yield) and 1 m<sup>3</sup> of harvested softwood.

Data from Agri-footprint v. 6.3 (Blonk et al., 2023) were used to determine GWP<sub>fossil</sub> and GWP<sub>biogenic</sub> (but not GWP<sub>LULUC</sub>) for oats and from ecoinvent (v 3.10) for harvested softwood (dataset details are presented in Table S6). N<sub>2</sub>O emissions from organic soils were included in GWP<sub>fossil</sub>, by using the emission factors 13 kg N<sub>2</sub>O-N/ha/year (IPCC, 2014) for oats and 0.92 kg N<sub>2</sub>O/ha/year for harvested softwood (Statistics Finland, 2023). For cropland, the N<sub>2</sub>O emissions associated with SOC losses on mineral soils were calculated according to IPCC (2006d) Tier 1. Life cycle impact assessment method used was GWP100 (IPCC, 2021). For oats, an economic allocation factor between grain and straw was used (0.856; Blonk et al., 2023), assuming an average oats yield of 3390 kg/ha. For harvested softwood, no allocation was used, and so, the LULUC emissions and removals were distributed equally for the average annual harvested wood in Finland on a volumetric basis, 3.31 m<sup>3</sup>/ha/year (Luke, 2023).

The average GWP<sub>LULUC</sub> estimates of cropland and forest land based on the year 2021 CRF table data were considered as a scenario called Finland average (Table 1). In the Finland average scenario, the same A<sub>min</sub> and A<sub>org</sub> were used for CL remaining CL and land converted to CL, and correspondingly for forest land (Table 1). This was decided because the A<sub>min</sub> and A<sub>org</sub> values derived from the National GHG Inventory represent a weighted average of remaining and converted land. The sensitivity of GWP for oats and harvested softwood was analyzed by adjusting the land use history and soil type shares from 0 to 1, as shown in Table 1.

### 3. Results

#### 3.1. Oats case study

In the Finland average scenario, GWP of oats included 40 % of GWP<sub>fossil</sub>, 0 % of GWP<sub>biogenic</sub>, and 60 % of GWP<sub>LULUC</sub> (Fig. 2). In the Finland average scenario, GWP<sub>LULUC</sub> consisted mostly (total 79 %) of organic soil SOC losses (Table 2). This was a result of the relatively high organic soil share, 11 %, of Finnish cropland in 2021 (Table S4). Most of the GWP<sub>fossil</sub> was related to N<sub>2</sub>O from N fertilisers, crop residues, and peat oxidation on organic soils, followed by GHG emissions from cultivation input production, e.g., fertilisers.

In the scenario with 100 % CL remaining CL, the total GWP of oats was 5 % lower than in Finland average scenario (Fig. 2), due to

**Table 1**  
Land use history and soil types for each of the scenarios.

	Scenario	A <sub>conv</sub>	A <sub>rem</sub>	A <sub>min</sub>	A <sub>org</sub>
Cropland (oats case study)	Finland average	0.94	0.06	0.89	0.11
	100 % CL remaining CL	0.00	1.00	0.89	0.11
	100 % land converted to CL	1.00	0.00	0.89	0.11
	100 % mineral soil	0.94	0.06	1.00	0.00
	100 % organic soil	0.94	0.06	0.00	1.00
Forest land (harvested softwood case study)	Finland average	0.005	0.995	0.73	0.27
	100 % FL remaining FL	0.00	1.00	0.73	0.27
	100 % land converted to FL	1.00	0.00	0.73	0.27
	100 % mineral soil	0.005	0.995	1.00	0.00
	100 % organic soil	0.005	0.995	0.00	1.00

CL = cropland; FL = forest land; A<sub>conv</sub> = share of land converted to a new land use category within the past 20 years (either land converted to CL or land converted to FL); A<sub>rem</sub> = share of land remaining in the same land use category (either CL remaining CL or FL remaining FL); A<sub>min</sub> = share of mineral soil area; A<sub>org</sub> = share of organic soil area.

decreased SOC losses on mineral soil. Mineral soil SOC losses on CL remaining CL were related to average LMCs on Finnish cropland, and historical LUCs that have occurred more than 20 years ago. In this case study, the inclusion of historical LUC impact was related to open-term amortization period of the Tier 3 method used in the National GHG Inventory (Table S1).

In the scenario with 100 % land converted to CL, especially the carbon stock losses in living biomass increased the total GWP of oats by 89 % compared with Finland average scenario. In the scenario with 100 % land converted to CL, weighted average value of different past land categories (i.e., forest land, grassland, wetlands, settlements, and other land) converted to cropland was used based on the year 2021 data from Finland.

The high contribution of organic soils in GWP<sub>LULUC</sub> was considerable as seen in the scenario with 100 % organic soil, in which the total GWP of oats was approximately 12-fold compared with the scenario with 100 % mineral soils. The increase was related to both carbon losses in organic soil SOC stock and N<sub>2</sub>O from peat oxidation (Table 2).

From 2000 to 2021, GWP<sub>LULUC</sub> of cropland in Finland varied between 2903 and 3521 kg CO<sub>2</sub>-eq/ha (Fig. S1). The annual variability was mostly due to the share of organic soils varying from 9 to 11 %, and the share of land converted to cropland out of total cropland varying from 3 to 6 % (Table S4).

#### 3.2. Harvested softwood case study

In the Finland average scenario, LULUC removals in GWP<sub>LULUC</sub> category were approximately five times higher than emissions in GWP<sub>fossil</sub> category (Fig. 3). This removal primarily resulted from increased carbon stocks in living biomass within the forest (Table 3), although the biomass carbon stocks of Finnish forests have shown a reducing trend over time (Fig. S2).

Sensitivity analysis results indicated that the GWP of harvested softwood was impacted significantly by both soil type and land use history, with soil type demonstrating a notably higher influence (Fig. 3). For instance, in the scenario with 100 % FL remaining FL, LULUC removals aligned closely with the Finland average scenario, given that around 99 % of forest land is categorised as forest land remaining forest land (Table S5). The maximal LULUC removals were resulted in the scenario 100 % land converted to FL (within the past 20 years). Scenario with 100 % land converted to CL considered the weighted average value of different past land categories (i.e., cropland, grassland, wetlands, settlements, and other land) converted to forest land based on the year 2021 data from Finland. In this scenario, LULUC removals were six-fold compared with the Finland average scenario. In the scenario with 100 % mineral soil, LULUC removals were two-fold that of the Finland average scenario. Conversely, in the scenario with 100 % organic soil, net LULUC emissions instead of net LULUC removal were observed, as the GWP<sub>LULUC</sub> was three-fold compared with GWP<sub>fossil</sub> (Table 3). The increase was attributed to CO<sub>2</sub> and N<sub>2</sub>O emissions from organic soils (Table 3).

From 2000 to 2021, GWP<sub>LULUC</sub> of forest land fluctuated between -2403 kg CO<sub>2</sub>-eq/ha in 2009 and -496 kg CO<sub>2</sub>-eq/ha in 2021 (Fig. S2). The annual variability in forest land was primarily attributed to changes in living biomass on forest land remaining forest land, which ranged from 690 kg C/ha in 2009 to 180 kg C/ha in 2021 (Table S5). In Finland, increase of the biomass carbon stock is a result of large-scale reforestation and development of forest management practices that followed a period of intensive forest harvest, which took place in the second half of the 20th century. Consequently, these actions resulted in overall GHG removal occurring during the end of the 20th century and the beginning of the 21st century. However, this long-term trend of Finland's carbon removals in forests is now weakening especially due to aging of forests and consequently, reduced growth (Vauhkonen et al., 2024). In addition to living biomass, SOC dynamics also showed variation between years, as SOC losses on organic soils increased and carbon removals in mineral soil SOC were reducing in 2000–2021 (Fig. S2). When the trends of

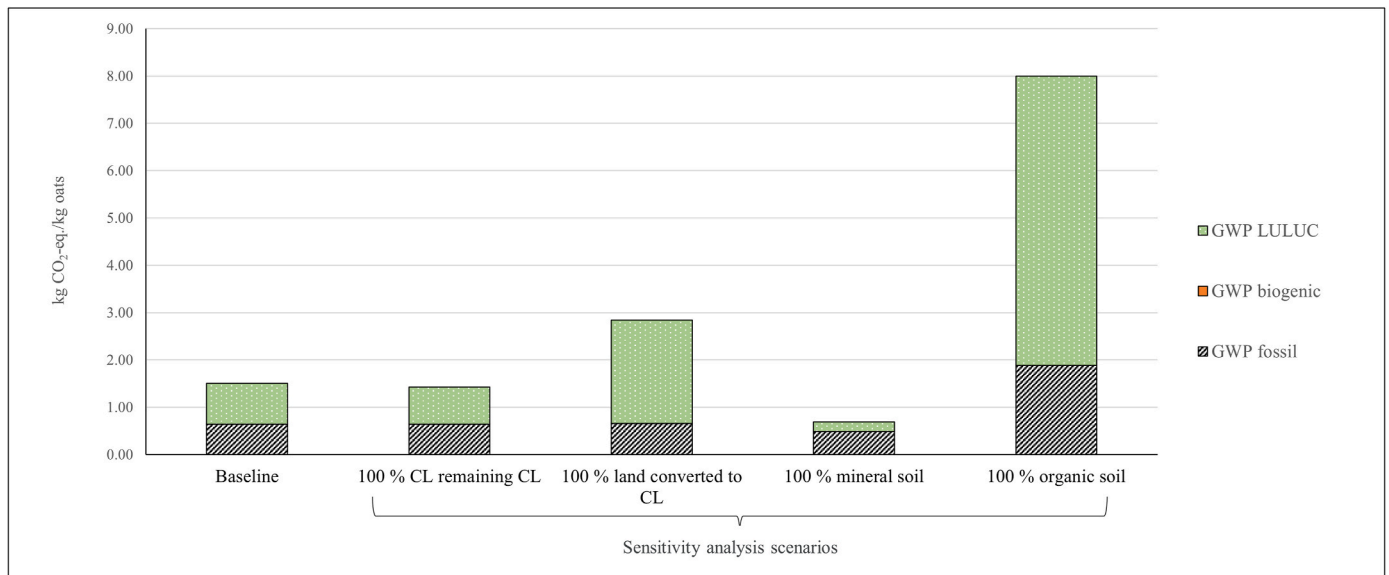


Fig. 2. GWP of 1 kg oats (cradle to farm gate) produced in Finland. Finland average = average cropland GWP<sub>LULUC</sub> in Finland (2021). Sensitivity analysis scenarios include modified shares of remaining cropland (CL) vs. converted cropland (within the past 20 years) and mineral vs. organic soil.

Table 2

Contributions of different emission sources in the GWP of oats. Values are presented as kg CO<sub>2</sub> eq/kg oats.

Emission source		Finland average	100 % CL remaining CL	100 % land converted to CL	100 % mineral soil	100 % organic soil
GWP <sub>fossil</sub>	N <sub>2</sub> O – N fertilisers and crop residues	0.18	0.18	0.18	0.18	0.18
	N <sub>2</sub> O – peat oxidation	0.15	0.15	0.15	0.00	1.41
	GHG from input manufacturing and transports	0.19	0.19	0.19	0.19	0.19
	Other GHG emissions	0.12	0.12	0.14	0.12	0.12
GWP <sub>biogenic</sub>		<0.01	<0.01	<0.01	<0.01	<0.01
GWP <sub>LULUC</sub>	living biomass	0.06	0.00	1.06	0.06	0.06
	SOC – organic	0.68	0.68	0.70	0.00	6.06
	SOC – mineral	0.13	0.11	0.41	0.15	0.00
	DOM	0.00	0.00	0.01	0.00	0.00
	CH <sub>4</sub>	0.00	0.00	0.00	0.00	0.00

CL = cropland, SOC = soil organic carbon, DOM = dead organic matter, CH<sub>4</sub> = methane emissions from organic soil.

reducing removals in living biomass, increasing soil carbon losses and limiting soil carbon sequestration are combined, the currently net negative GWP<sub>LULUC</sub> of Finnish forest land may reduce or turn into net emission in the future.

#### 4. Discussion

Despite several efforts, there has been no consensus on methodological frameworks for evaluating GWP<sub>LULUC</sub> due to undesirable consequences of linear pathways and time perspectives (Leinonen, 2022; Sazdovski et al., 2024). For instance, Brandão et al. (2013) compared six different methods and found that the value choices are not purely based on science. Commonly used approaches for biogenic carbon, within which GWP<sub>LULUC</sub> may also be considered, include 0/0, +1/-1 method, and dynamic LCA (Guest et al., 2013; Pawelzik et al., 2013). De Rosa et al. (2017a) developed a global LULUC database with country-specific matrices by merging remote sensing global land cover datasets, the Forest Resource Assessment, and FAOSTAT datasets. The choice of methodological approaches is influenced by factors such as inclusion of indirect land use changes, selected climate indicators, time horizons, and climate matrices (De Rosa et al., 2018). Considering the importance of a time-dependent approach, De Rosa et al. (2017b) developed a parametric model to evaluate carbon fluxes for time-dependent LULUC assessment of bio-based products.

In this study, we developed an easy and flexible method to quantify GWP<sub>LULUC</sub> on product level, following basic mass balance principles based on the general framework by Leinonen (2022), and using openly accessible data. The key element of the developed framework is the improved linkage between annually updating national-level data open for all LCA practitioners and therefore, improved usability and accessibility of GWP<sub>LULUC</sub> calculation. The developed framework specifies the existing methodological guidelines to equation level in the context of agriculture and forestry. It supplements LULUC emission and removal calculation by differentiating mineral and organic soils and considering both net removals and emissions instead of only emissions, thus aligning with ISO 14067 (ISO, 2018). Furthermore, consideration of both converted and remaining land carbon stocks aligns with GHG protocol (2022), ISO 14067 (2018) and EF methodology (European Commission, 2021). Another benefit of the framework is the full coverage of all land-related carbon stocks – living biomass, DOM, and SOC, as required by GHG protocol (2022).

National-level average estimates of carbon stock changes per hectare were used within the framework, as the national level is in most cases specific enough to provide more accurate LULUC estimates, while it is also general enough to avoid need for complex and very detailed activity data. Thus, the national level is a compromise between certainty and applicability, within the limits of data and expertise of LCA practitioners (Goglio et al., 2015). Furthermore, the framework applies a centralised

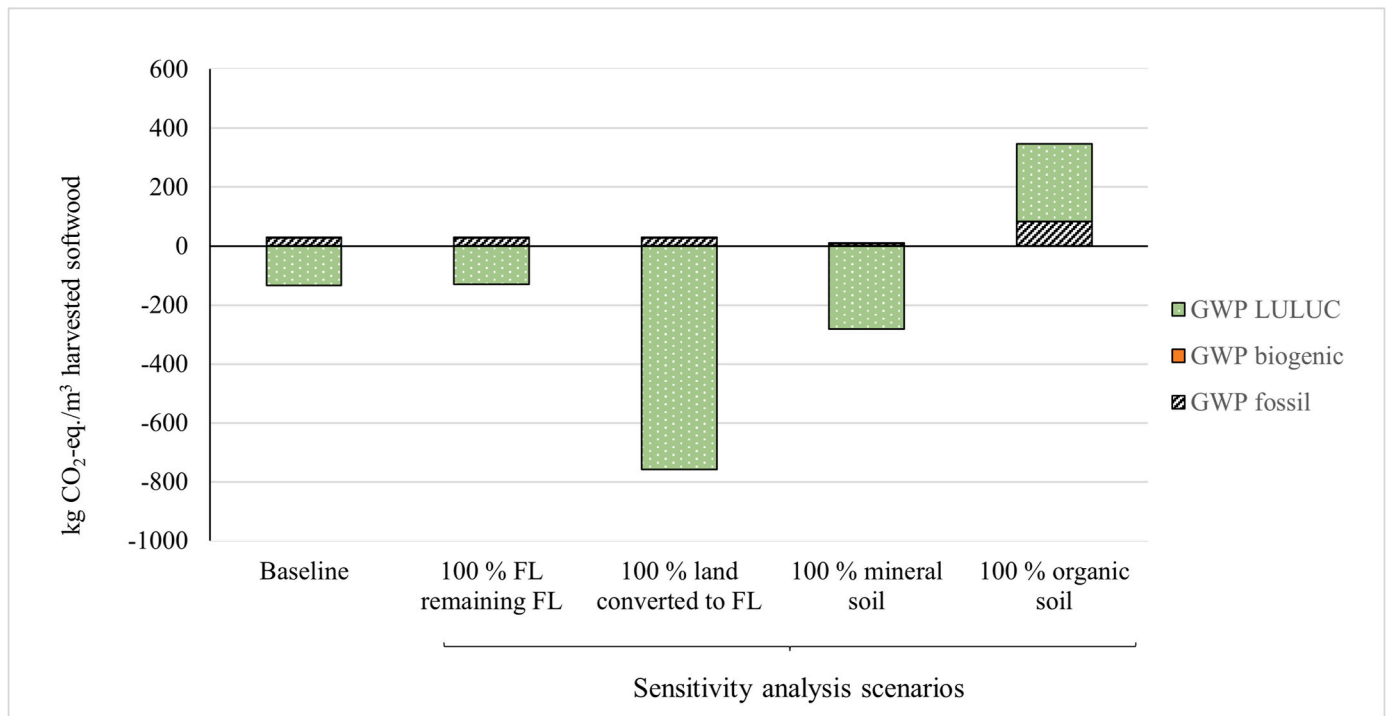


Fig. 3. GWP of 1 m<sup>3</sup> harvested softwood (cradle to harvested product) produced in Finland. Finland average = average forest land GWP<sub>LULUC</sub> in Finland (2021). Sensitivity analysis scenarios include modified shares of remaining forest land (FL) vs. converted forest land (converted within the past 20 years) and mineral vs. organic soil.

Table 3

Contributions of different emission sources in the GWP of harvested softwood. Values are presented as kg CO<sub>2</sub> eq/m<sup>3</sup> harvested softwood.

Emission source		Finland average	100 % FL remaining FL	100 % land converted to FL	100 % mineral soil	100 % organic soil
GWP <sub>fossil</sub>	Fuel used in harvesting operation	6.04	6.04	6.04	6.04	6.04
	Fuel used in other machinery	1.06	1.06	1.06	1.06	1.06
	N <sub>2</sub> O – peat oxidation	20.67	20.67	20.67	0.00	75.35
	Other GHG emissions	0.90	0.90	0.90	0.90	0.90
GWP <sub>biogenic</sub>		0.02	0.02	0.02	0.02	0.02
GWP <sub>LULUC</sub>	living biomass	-203.28	-198.89	-1120.35	-203.28	-203.28
	SOC – organic	111.75	110.55	361.26	0.00	409.41
	SOC – mineral	-57.25	-57.40	-26.57	-78.75	0.00
	DW	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>
	Litter	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>	0.00 <sup>a</sup>
	CH4	15.67	15.61	26.97	0.00	57.39

FL = forest land, SOC = soil organic carbon, DW = dead wood, CH4 = methane emissions from organic soil.

<sup>a</sup> Included in SOC in the National GHG Inventory of Finland.

top-down approach instead of a bottom-up approach, since top-down is more suitable for national-level estimates of LULUC emissions and removals.

Within the framework, LUC is determined similarly to IPCC (2006a), since we do not see that a shift from annual to perennial crops (or vice versa) is a LUC, but rather a LMC. That is because both annual and perennial crops are typically both within cropland category, and because the same cropland area may be used for annual and perennial crop cultivation on different years with fluctuation back and forth. Also, according to Goglio et al. (2015), LMC does not cause a permanent change in land cover. Because we considered the changes between annual and perennial cropland as LMC instead of LUC, our framework differs from the PAS2050:2011 method (BSI, 2011), used in the Blonk LUC tool (de Weert et al., 2023) and Agrifootprint (Blonk et al., 2023) and Ecoinvent (2023) databases for LCA. However, if perennial crops are considered as IPCC category grassland or any land use category other than cropland, then, the shift between annual and perennial crops is a LUC. In more detailed assessments than national level (e.g. field-level

assessments), consideration of annual and perennial cropland separately is very important, as perennial cropland has been shown to have potential for increased SOC stocks compared with annual crops (Heikkinen et al., 2022).

The developed framework differs from PAS2050:2011 which accounts only for LUC-related emissions and only in the 20 initial years after a LUC (=fixed-term amortization period). The use of either fixed-term or open-term amortization period was chosen to align with the National GHG Inventories, and further to improve the possibilities to obtain open-access national-level data.

The use of national average GWP<sub>LULUC</sub> for cropland and forest land based on the latest available country-specific CRF table data is suggested to account for the average national-level LULUC emissions and removals. However, as in the case study, the GWPs of oats and harvested softwood were highly sensitive to organic soil share, varying from -160 % to +440 % compared to the Finland average GWPs. Therefore, in areas high in organic soils such as Finland, collection of primary data for A<sub>min</sub> and A<sub>org</sub> is recommended to represent the production chain better

compared to national-level average  $A_{\min}$  and  $A_{\text{org}}$ . This is because organic soils are often aggregated in specific areas. For example, in Finland, organic soils are located especially in Northwest and Northern Finland (Kekkonen et al., 2019). Therefore, regional-level or other more detailed estimates for  $A_{\min}$  and  $A_{\text{org}}$  can also be used if the origins of the material can be traced. However, if more detailed data on  $A_{\min}$  and  $A_{\text{org}}$  is not available or the origins can not be traced to regional level, LULUC emission and removal estimates at the national level are the most accurate estimates available. In addition to organic soils, also land use history (converted vs. remaining land) was shown to cause marked variation in  $\text{GWP}_{\text{LULUC}}$  of oats and harvested softwood. Therefore, regional-level or more detailed data for  $A_{\text{conv}}$  and  $A_{\text{rem}}$  are beneficial, although the data to be used depends on the scope of the specific LCA study.

In LCA studies with a smaller scope than a national level, accounting for LMCs can be targeted. The framework described here is not meant to assess the effect of specific LMCs on LULUC emissions and removals, but rather to represent an average agricultural and forestry management on a national level. Regarding the LMCs to be considered in the future in agricultural and forestry LCAs, there are several interesting management methods. For example, water table management has shown great potential to reduce GHG emissions on agricultural organic soils (Regina et al., 2015; Lehtonen et al., 2023). Also, net carbon sequestration in mineral soils following for example cover cropping (Joensuu et al., 2022) and cultivation of perennial crops (Heikkinen et al., 2022) has potential to mitigate agricultural GHG emissions. In the forest sector, for example, harvesting level (Mäkelä et al., 2023), collection of energy wood from final felling (Akujärvi et al., 2021), and excluding needles during whole-tree harvesting (Mäkipää et al., 2015) influence carbon stocks in living biomass and soil. To account for such agricultural and forest management methods, more LCA method development is needed. However, to develop, apply, and test such models, comprehensive empirical data and further research efforts are needed (Ogle et al., 2010).

## 5. Conclusion

Inclusion of all LULUC emissions and removals comprehensively enhances the transparency and reliability of LCA results and helps to avoid partial or double counting. In this study, a framework was developed for integrating national-level LULUC emissions and removals into LCA of agriculture and forestry products, aligning with and supplementing existing methodologies and guidelines. The framework enhances comprehensive accounting of land carbon stocks, including SOC losses from organic soils, and the utilization of open-access national-level average data to improve practicality and accessibility.

The use of the framework was demonstrated by applying it to the production of oats and harvested softwood in Finland. In conclusion, it was found that LULUC emissions and removals make a substantial contribution to the GWP of chosen agricultural and forestry products and that the effects were highly dependent on the share of organic soils in the production chain. Furthermore, the share of organic soil and land use history within the production chain can be specified if the scope of the specific study is, for example, regional level or other level more detailed than the national level. In the future, LULUC emissions and removals based on regional-level average data could be produced. Also, LULUC emissions and removal estimation methods to account for LMCs in LCA need to be developed further in the future.

## CRedit authorship contribution statement

**Anniina Lehtilä:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Hafiz Usman Ghani:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Xing Liu:** Writing – review & editing, Visualization, Project administration, Investigation. **Taru Palosuo:**

Writing – review & editing, Validation. **Hanna L. Tuomisto:** Writing – review & editing, Validation. **Ilkka Leinonen:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgment

This research was supported by several projects: LCAFoodPrint, funded by the Ministry of Agriculture and Forestry of Finland (VN/7881/2020); Modi-LCA, funded by Business Finland (8685/31/2021); and Bio-LCA, also funded by Business Finland (6873/31/2021). We are grateful to the funders for their support. We would like to extend our thanks to Jaakko Heikkinen and Tarja Silfver from the Natural Resources Institute of Finland (Luke) for their invaluable guidance.

## Abbreviations

CL	Cropland
DOM	Dead organic matter
FL	Forest land
GWP	Global warming potential (100 years)
LB	Living biomass
LMC	Land management change
LUC	Land use change
LULUC	Land use and land use change
SOC	Soil organic carbon

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2025.144999>.

## Data availability

Data will be made available on request.

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