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Greenhouse gas (GHG) emissions and removals in the Finnish forest sector over scope 1, 2, and 3

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ABSTRACT

Forests play a central role in the Finland's bioeconomy strategy and are key to addressing climate challenges and achieving national climate neutrality targets. In this context, quantifying the forest sector's total emissions is essential for supporting effective and evidence-based climate-mitigation planning. This study develops a framework to evaluate the life cycle greenhouse gas emissions of Finland's forest sector for the year 2023 using an organizational carbon footprinting approach that combines top-down and bottom-up methodologies, and aligned with the Scope 1, Scope 2 and Scope 3 structure. The total life cycle GHG emissions from Finnish forest sector were approximately 8.4 Mt CO_2e. Organic soils are the largest contributors, followed by processing of exported products, upstream emissions from pulp and paper production and transportation of exported items. Most of the emissions originate from Scope 3 sources (approximately 68%), primarily associated with materials and suppliers over which forest-sector stakeholders have no direct control. This was followed by Scope 1 emissions (around 27%) and Scope 2 emissions (around 5%), which together represent roughly 11% of Finland's total energy-related emissions. Land use, land-use change, and forestry (LULUCF) in Finland's forest sector result in a net removal, with a value of -0.38 Mt CO_2 eq. The developed framework provides a comprehensive assessment by identifying both chain-specific and scope-specific emission contributions. It also supports annual updates and can be adapted to different geographic regions. Such an approach would offer policy makers a clearer understanding of the forest sector's role in meeting national and international climate change mitigation targets.

1. Introduction

Human activities are increasingly threatening the stability of the Earth system, with six of the nine planetary boundaries already transgressed (Richardson et al., 2023). In response, the bioeconomy has emerged as a promising pathway for addressing climate challenges and meeting mitigation targets by replacing fossil-based systems with bio-based resources (EUSTAFOR, 2017). The forest sector is central to this transition and represents a long-standing example of a bio-based circular economy, producing recyclable materials and converting processing side streams into value-added products.

Forest land covers approximately 74% of Finland – substantially higher than the European Union average of around 40% (Luke, 2023) – and plays a pivotal role in national climate mitigation efforts. Over the long term, living biomass on Finland's forest land has acted as a net greenhouse gas (GHG) removal (Luke, 2024a), supporting both the EU's 2050 climate neutrality target and Finland's 2035 goal (Chiti et al., 2024; European Commission, 2020; State Treasury 2025). The Finland's Bioeconomy Strategy 2022–2035 sets ambitious objectives to double value addition and accelerate the green transition (Finnish Government, 2022). In 2024, Finnish bioeconomy generated an output of around €86 billion, representing about 16% of national output, with €23 billion in added value. The sector employed roughly 309,000 people (11% of the national workforce), of whom about one fifth (i.e., 61,000) worked in the forest sector (Luke, 2024a).

Bio-based products do not always result in lower GHG emissions compared to fossil-based products, as their performance depends on factors such as feedstock origin, land-use change impacts, production pathways, end-of-life treatment. This underscores the need for a comprehensive life cycle based assessment (EEA, 2021; Tang et al., 2024; Zuiderveen et al., 2023). The current national GHG inventory in Finland follows the IPCC framework, which accounts for annual flows but does not allocate emissions or removals to the forest sector. Conversely, Life Cycle Assessment (LCA) provides sector-specific, cradle

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to grave accounting but does not align with national boundaries. Although LCA studies exist for individual Finnish forest products or a combination of these products (e.g., Alam et al. 2022; Corcelli et al., 2018; Wüstenhagen and Krombholz, 2023), comprehensive assessments covering the entire forest-sector supply chain remain lacking.

This gap is partly due to the absence of suitable methods for integrating environmental impacts into existing statistical system. One proposed solution has been the Input-Output approach (e.g., Karhinen et al., 2025). However, this method presents several challenges, as highlighted in the JRC technical report on the bioeconomy (Kuosmanen et al., 2020). It cannot differentiate between the environmental impacts of bio-based and fossil-based activities within the same industry, nor can it account for the potential carbon sequestration associated with bioproduction. In addition, it is unable to capture how system-level changes influence sector-specific emissions. As a result, when applied in practice, the approach implies that the only verifiable way to reduce environmental impacts is to reduce production. A more detailed and differentiated assessment framework is therefore needed to evaluate environmental impacts accurately and to identify meaningful mitigation opportunities.

In this study, we applied a production chain-specific life cycle assessment (LCA) methodology to analyze the environmental impacts of the forest sector. This approach captures distinct processes, material flows, and emission sources across forest-based value chains. Based on this, this study evaluates the life cycle GHG emissions of Finland's entire forest sector by combining top-down (i.e., allocation of national-level emissions or removals) and bottom-up (i.e., upscaling process-level emissions and removals) analytical techniques (Ghani et al., 2025). This hybrid approach, combining top-down and bottom-up methods, is not new. For example, hybrid LCA combining process based LCA and input output analysis has been suggested for system boundary selection (Suh et al., 2003) and Scope 3 emissions inventories (Lee and Ma, 2013). More recent studies have applied this approach to overcome data limitations (Weinold and Majeau-Bettez, 2026) and to expand system boundaries (Gamarra et al., 2023), among others. Therefore, we have also used this hybrid approach to improve data availability within our selected system boundaries and scope-level assessment.

The intent of this study is to complement existing forest bioeconomy statistics through a high-level analysis of biomass flows using established input data from authoritative sources and averaged process parameters. Furthermore, the methodological framework is designed to support advocacy at the European Union level in the context of the forthcoming EU bioeconomy strategy, to strengthen national statistical systems, and to encourage the adoption of similar assessment approaches across other EU member states.

2. Methodology

2.1. Analytical framework and system boundary

2.1.1. Analysis framework

The objective of this study was to evaluate the life cycle greenhouse gas (GHG) emissions and removals associated with Finnish forest sector for the year 2023. The analysis followed organizational carbon footprinting principles and was structured according to Scope 1, Scope 2 and Scope 3 categories (Greenhouse gas protocol, 2021; ISO, 2006a, b), ensuring methodological rigor and consistency. The Scope 1 emissions represent the direct emissions from sources located within Finland. Scope 2 includes indirect emissions from the generation of purchased energy, while Scope 3 emissions are all other indirect emissions (not included in scope 2) occurring along the value chain, both upstream and downstream. This assessment was performed alongside the existing national GHG statistics for forests and the energy sector, with the aim of complementing and strengthening national reporting frameworks.

The framework integrates life cycle assessment (LCA) methods, national statistics, and national GHG inventory data to quantify the carbon footprint of the forest sector (Fig. 1). A bottom-up approach was applied to model emissions from individual processes within forest-based production chains, capturing both direct and indirect emissions. Sector-level impacts were evaluated by aggregating contributions from individual actors and processes. To ensure completeness, the bottom-up analysis was combined with a top-down method for integrating national greenhouse gas inventory results on forest-based land use, and land use change and forestry (LULUCF) emissions and removals and results on direct sector-specific industrial fuel consumption emissions. This approach enables alignment between process-level assessments and national-level reporting. As highlighted by Brandão et al. (2025), the national GHG inventories are based on retrospective, average emission values, and do not capture the future effects of possible changes in product demand. Such changes would require consequential assessment, including indirect land use changes, as demonstrated e.g., by Kallio and Garvik (2026). Since the purpose of the current framework is to provide a snapshot of the emissions of a certain, foregone year, indirect land use changes were outside of the scope of the study. The framework is designed to be annually updatable and applicable also to other bioeconomy sectors, thereby supporting the continued development of Finland's bioeconomy monitoring systems.

2.1.2. System boundary

The system boundary of the Finnish forestry product system (Fig. 2) includes both wood raw material grown domestically in Finland and wood imported from other countries, along with their subsequent industrial processing into final products. The transportation system incorporates domestic transport within Finland, international sea freight for import and exports, and freight transport associated with import and export of wood.

The production processes for wood products originating from Finnish forestry include silviculture operations—such as site preparation, plantation, and stand management—and harvesting operations, including thinning, final felling, and forwarding to the roadside. Additionally, domestic forest-based LULUCF emissions and removals are accounted considering CO_2 uptake and release, determined by variations in carbon stock, and methane (CH_4) and nitrous oxide (N_2O) emissions. Parallel estimations are made for imported wood based on the forestry conditions in the countries of origin. Emissions related to wood processing for final products are also included, covering the transformation of sawlogs into sawn timber and panels, and pulpwood into pulp, followed by further pulp processing into paper and cardboards, for the total volume of wood utilized in Finland. For exported products, emissions associated with transport and pulp processing into paper and cardboards were considered in the calculations.

The starting point of the analysis was the quantification of wood flows using statistical data describing the supply and utilization of wood raw material in forest industry, based on mass balance principles. These data were obtained from annually updated statistics from the Natural Resources Institute Finland (Luke, 2024a), providing detailed information on wood-based dry matter flows across supply chains. To enable the calculation of total life cycle GHG emissions, mass specific characterization factors were derived for each process within the production chain. A concise overview of these calculations is provided in the following sections.

2.2. Calculation methods

The calculation of GHG emissions for the Finnish forest sector in 2023 was based on current inventory data from the Natural Resources Institute Finland (Luke, 2024b). Emissions associated with forest-product use were quantified using a life cycle assessment (LCA) approach (Table 1). Total GHG emissions refer to the emissions from upstream activities, primary (on-site) emissions, and from downstream processes.

The assessed life cycle stages encompass forestry operations and

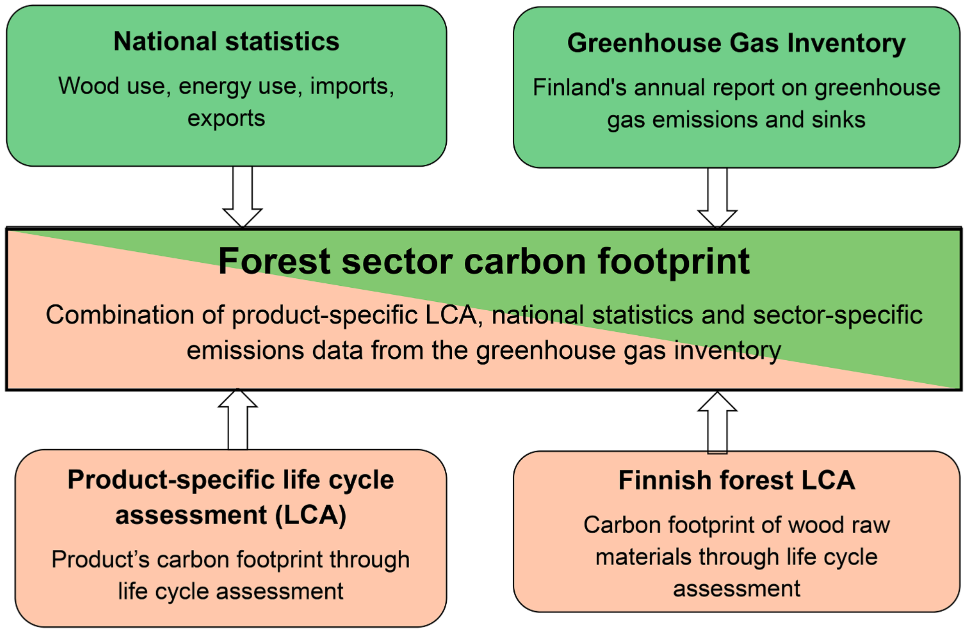

Fig. 1. Framework for forest sector carbon footprint accounting in Finland utilizing top-down (National statistics and Greenhouse gas inventory) and bottom-up (product-specific and forest LCA) approach.

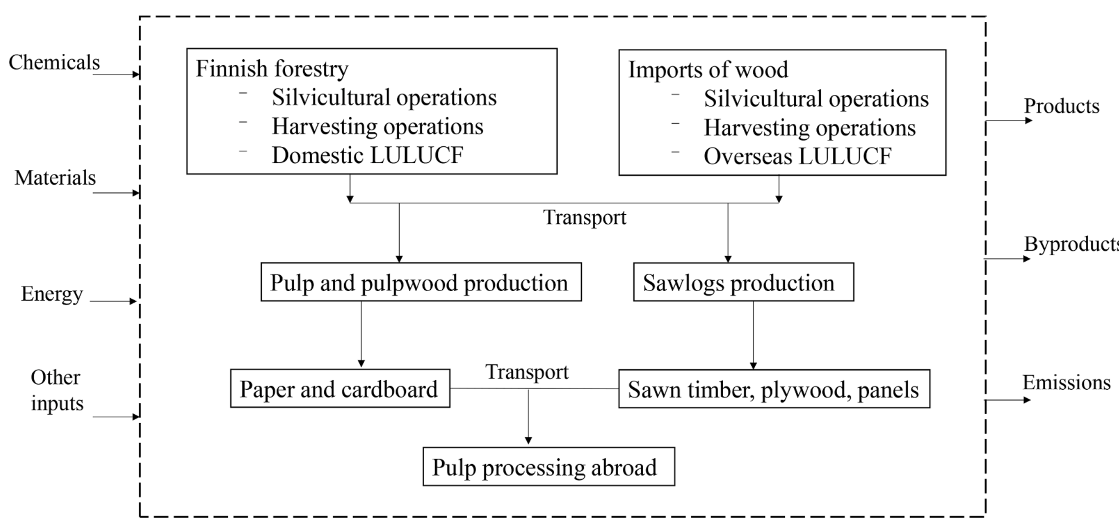

Fig. 2. System boundary of Finnish forestry product system.

Table 1
Forest product use in Finland for the year 2023 (Luke, 2024b).

Products	Dry matter of wood-based material, Mt
Harvested Sawlogs & pulpwood	26
Sawn timber	4.3
Wood panels and plywood	0.52
Pulp	8.30
Chemical pulp	6.30
Mechanical pulp	2.00
Paper and cardboard	4.84
Printing and writing paper	1.31
Tissue and others	0.68
Cardboard & packaging	2.84

harvesting, as well as the industrial processing of wood into solid wood products, pulp and paper. Emissions sources and data input for each process are summarized in Table 2. These stages collectively represent the major components of the Finnish forest-sector value chain and form the basis for calculating sector-wide GHG emissions.

Emissions for specific products were calculated by combining emissions from electricity use, fuel consumption, and the life cycle emissions of raw materials used in the processing. These materials include, for example, chemicals used in pulp industry, and adhesives such as glue or phenolic resin used in the wood-products industry. Data on wood material flows, obtained from Luke statistics (see Table 1), represent quantities of dry wood matter within the materials.

LULUCF carbon sinks and emissions from Finnish forests were sourced directly from the national greenhouse gas inventory complied by Luke. In addition, data on fuel consumption and associated emissions in pulp and paper industry, as well as in the sawn timber and wood panel industries, were also obtained from the national greenhouse gas inventory produced by Statistics Finland. These values represent only direct emissions from fuel use. To estimate scope 3 fuel related emissions, total fuel consumption associated with scope 1 emissions was

Table 2
Emissions and data sources across various processes.

Process	Input Data Source	References
Domestic LULUC (forest biomass, soil, wood products)	Luke GHG inventory	Luke, 2024b
Forestry activities	Luke life cycle inventory	Ecoinvent documentation, 2025
Domestic transport	Luke life cycle inventory	Statistics Finland, 2025a
Pulp and paper: fuels	Statistics Finland	Statistics Finland, 2025b
Pulp and paper: electricity	Finnish Forest Industries Federation, Statistics Finland	Personnel communication 2025; Statistics Finland, 2025b
Pulp and paper: materials	Ecoinvent, Wood flow statistics, literature review	Wernet et al., 2016; Corcelli et al., 2018
Sawn timber, plywood, boards: fuels	Statistics Finland, literature review	Statistics Finland, 2025c
Sawn timber, plywood, boards: electricity	Statistics Finland, Wood flow statistics	Räty and Jallinoja, 2021; Statistics Finland 2025c; Luke, 2024b
Sawn timber, plywood, boards: materials	EPDs, Ecoinvent, Wood flow statistics	Ecoinvent 2025; International EPD system, 2025; EPD International AB 2021, 2022, 2023, 2024; EPD hub, 2025; Räty and Jallinoja, 2021
Imports: transport	Luke statistics	Luke, 2025
Imports: processes	Wood flow statistics, Ecoinvent	Luke, 2025; Ecoinvent, 2025
Imports: LULUCF	Luke statistics, GHG inventory results	Luke, 2025; NIR, 2025
Exports: transport	Luke statistics	Luke, 2025
Exports: processes	Luke statistics, Ecoinvent	Ecoinvent, 2025; Luke, 2025

multiplied by a coefficient of 0.28. This coefficient reflects the ratio of scope 3 to scope 1 emissions, calculated as a weighted average based on the industry's consumption of different fuel types. All remaining emissions were calculated using appropriate emission factors, which were multiplied by the corresponding quantities of materials used in Finland (Table 1). Emissions values are reported in megatons of carbon dioxide equivalent (Mt CO_2e).

Detailed descriptions of each activity and the methodologies used for emission calculations are provided in Section 2.3–2.10.

2.3. Domestic LULUCF sector

In this study, the LULUCF emissions and removals consider the GHG balance of forest land (including living plant biomass and mineral and organic forest soils) and the GHG balance of the harvested wood products. These carbon removal and emissions were derived from data presented in the National Inventory Report of Finland (NIR, 2025). Emissions and removals were calculated according to the IPCC Guidelines (IPCC 2006; IPCC 2019). According to the national inventory, tree biomass includes above-ground components (stem wood, stem bark, living and dead branches, and needles or foliage) and below-ground components (stumps and both coarse and fine roots). Carbon stock changes in living tree biomass are reported as combined national estimate for above- and below-ground biomass pools.

Carbon stock changes in mineral and organic soils are estimated for deadwood, litter and soil organic matter to a depth of one meter. Organic forest soils (peatlands) are classified according to the National Forest Inventory (NFI) criteria. A site is designated as peatland if the organic soil layer consists of peat, or if >75% of the ground vegetation is characterized by peatland-specific species. Carbon emissions are estimated for drained peatlands, while undrained peatland soils are excluded from the inventory.

Carbon stock changes in harvested wood products (HWP) are based on production-based stocks (IPCC, 2006, 2019) for wood harvested in Finland. These stocks are categorized into harvested wood products produced and consumed domestically, and those produced domestically but exported abroad. In the calculations, sawn timber and veneer sheets are differentiated by tree species (spruce, pine, and birch), while plywood is categorized into spruce and birch types. Wood-based panels are classified into veneer sheets, plywood, and particle and fibre boards, with fibre board further divided into high-density fibreboard (HDF), medium-density fibreboard (MDF), and low-density fibreboard (LDF). Conversion factors from volume units to carbon were applied following Hamberg et al. (2016).

2.4. Forestry activities

A life cycle inventory (LCI) was conducted for forestry activities in Finland (Table 3). The inventory includes a comprehensive range of silvicultural and forest improvement operations, including soil preparation, regeneration, and young stand management. Key silvicultural interventions such as fertilization, thinning, and final regeneration felling were incorporated up to the point where the harvested timber is prepared for transportation ("ready at roadside"). Relocation of harvesters and forwarders between the logging sites were also included in the estimation. This systematic inventory was averaged over 2018–2022 and captures energy and material inputs, emissions, and resource flows associated with each stage of forest growth and management, facilitating detailed environmental assessments of Finnish forestry operations. The inventory was done during 2024–2025, and currently available in Ecoinvent v3.12 (see Ecoinvent documentation, 2025). In addition, the fertilization inventory (kgN per m3) for mineral soil is estimated based on the total fertilized area in Finland, of which approximately 73% consists of mineral soils (NIR, 2025). A nitrogen application rate of 150kgN per ha was assumed, consistent with Finnish practice (Routa et al., 2011).

The emission factor for harvested wood was calculated as t CO_2 per m^3 of wood by adding emissions for all activities in forest and for long distance transportation.

2.5. Domestic transport

Data on transported mass, vehicle mileage and transport distance for domestic road transport were collected from Statistics Finland (Appendix, Table A1). Solid wood products (sawn timber and wood-based panels) were assumed to be transported using 76-ton trucks, whereas other products (e.g., chemical, pulp and paper items) were transported using 60-ton truck capacity with variable load ratio (64–96%) and transport distances (89–196 km), implying logistics of Finnish forest sector and aligned with national transport statistics.

Fuel consumption estimates were derived from the LIPASTO database (See Appendix, Table, A1–A2, VTT, 2017), which provides emissions factor and energy-use data for Finnish road transport. All goods were assumed to be transported by truck. Emissions from diesel consumption were associated with the truck's load ratio for both the loaded

Table 3
Technosphere exchanges for one cubic meter of wood harvested in Finland.

Forest Management activities	Units	Inventory values
Tree seedling, for planting	unit	1.30
Diesel burned in silvicultural activities	MJ	4.30
Gravel, crushed	kg	25.99
Harvesting, forestry harvester	hour	0.051
Forwarding, forwarder	hour	0.056
Diesel for relocation of harvester & Forwarder	kg	5.45
Fertilization for growth	kg N	0.078
Energy wood harvesting	hour	0.0098
Piling and forwarding	hour	0.00018

trip and empty return trips. Total transportation impacts were calculated by multiplying tonne-kilometres (tkm) for loaded trips or milage for empty rides (Appendix, Table, A1) by the corresponding emission factors (Appendix, Table, A2).

2.6. Pulp and paper

Total fuel consumption in pulp and paper production was collected from Statistics Finland (2025b). Electricity demand was sourced from Finnish Forest Industries, based on the Finnish Energy statistics. Materials and chemicals input used in pulp production were modelled using the data from the Kemi pulp factory (Metsä Fibre Oy, 2019, see Appendix Table A3). These inputs were multiplied with the corresponding global warming impacts factors from the Ecoinvent v3.11 (Wernet et al., 2016) database to derive emissions per ton of pulp produced.

In our inventory, data are categorized for three different categories of paper and cardboards (Table 1). Materials inputs for printing and writing papers were quantified using data from Corcelli et al. (2018), based on inventories from Stora Enso's Kemi facilities (Appendix Table A4) in Finland. Inputs quantities were multiplied by global warming impact factors from the ecoinvent v3.11 Cut-Off system inventory with infrastructure. For the remaining two product categories "Tissue and others" and "Cardboard and packaging" material-related impacts were obtained directly from ecoinvent datasets. Only for material-related emissions were taken from ecoinvent, as emissions from energy use were calculated separately using national inventory data.

2.7. Sawn wood and wood panels

Fuel consumption for sawmills and wood-based panel production was collected from Statistics Finland. For sawn timber, average electricity demand was derived from five Finnish sawmills (Räty and Jallinoja, 2021), with an inventoried value of 154 kWh per ton sawn timber. Raw material inputs included 0.233 kg of lubricant and 0.289 kg of glue per ton of sawn timber.

Wood panel and plywood production uses wood and phenolic resin as raw materials. Electricity demand for these products was 232 kWh per dry ton (Puettmann et al., 2016). Phenolic resin requirements were calculated using environmental product declaration (EPD) published for Finnish plywood by companies such as UPM, Metsäwoodand, and Koskisen (EPD hub 2025; EPD international AB 2021; 2022; 2023; 2024). An average value of 0.09 ton resin per ton of plywood or wood panel was used in the calculations.

2.8. Wood import

Emissions related to LULUCF for imported wood were calculated separately from those within Finland. Sea and road transportation as well as forestry activities occurring outside Finland were assessed independently. This segregation allowed for the precise allocation of carbon emissions to each stage of the supply chain and ensured a comprehensive accounting of emission sources, from production in the country of origin to international and domestic transportation and processing activities.

Most forestry products imported into Finland originate from European countries. In addition, substantial volumes of pulp are imported from Latin America, particularly Brazil (Statistics Finland, 2025a, Appendix Table A5).

Impacts associated with foreign forestry activities were obtained from the ecoinvent market activities of each region. Silviculture, harvesting and forwarding emissions were inventoried for all 4.775 million m^3 of imported roundwood. The main import countries were Sweden, Estonia, Lithuania, and Latvia. Due to geographical proximity and the absence of Baltic countries' market activities, they were assessed using Swedish forestry market datasets. Total impacts were calculated by multiplying the inventoried volumes of each species by the corresponding impact factors and adding the sea freight emissions. Average transport distances from difference continents to Finland ranged from 1 700 to 25 000 km, based on google distance data (Appendix Table A6).

The LULUCF related GHG emissions and removal for imported wood were calculated using the framework developed by Lehtilä et al. (2025). A top down approach was applied, in which forest land related LULUCF emissions and removals over a specified period were equally allocated across the annual harvested biomass to derive the characterization factors (CFs) for each country. Methane (CH_4) emissions from organic soils were included in the LULUCF emissions CFs.

Data on changes in carbon stock in forest land, including land remaining in the same category and land converted from other land-use categories, along with CH_4 emission factors, and mineral and organic soils across different countries, were obtained from the common reporting format tables of national inventory submissions (UNFCCC, 2023). These tables are an open-access, annually updated database, which enables regular updates, for example, for the development of annual statistical databases. Data on wood harvesting were obtained from FISE (2022), UKWPT (2022), and UNECE (2022).

2.9. Wood export

2.9.1. Transportation

Emissions related to the logistics of exported wood including sea freight and domestic road transport (assumed distance 200 km) were estimated using distance data obtained from google datasets (Appendix Table A7-A8). Average transport distances from Finland to difference global regions ranged from 1 700 to 25 000 km. The impact calculation followed the same principles applied for assessing wood import, ensuring methodological consistency across international supply-chain flows. Transport emissions were calculated by multiplying tonne-kilometres (tkm) for sea and road transport by the corresponding emission factors provided in the Appendix.

2.9.2. Processing of pulp

To estimate the quantity of paper produced from the exported pulp, the exported pulp volume was multiplied by a conversion factor of 1.12 (Luke 2025), resulting in an estimated 4.98 Mt of paper. It was assumed that the exported pulp is evenly distributed between the production of printing paper, and cardboard and packaging materials. Emission factors for these downstream processes were sourced from the ecoinvent database. To avoid doble counting, emissions associated with pulp production and transportation were excluded, as these stages were already accounted for elsewhere in the analysis.

2.10. Calculation of electricity emissions factor

The electricity emissions factor (t CO_2e per MWh) for Finland was estimated by multiplying the share of each electricity-generation sources by its corresponding global warming impacts. The share of electricity sources was collected from Statistics Finland (2025c, see Appendix Table A9), while emission impacts were taken from the ecoinvent (2025) database.

3. Results

The Finnish forestry sector relies heavily on domestic resources, with a substantial share of wood and wood-based products is exported to international markets. In 2023, Finland produced 61.3 million m^3 of roundwood, of which 1.7 million m3 were exported, while 2.9 million m^3 were imported. Domestic production of sawn timber and plywood totalled 11.54 million m^3, 80% of which was exported, while imports totalled 0.29 million m^3. Among processed products, pulp and paper represented the most significant export categories. Domestic chemical pulp production reached about 7 Mt dry matter of pulp, with 67%

exported. Paper and cardboard production amounted to 6.3 Mt dry matter of paper, of which 94% were exported, leaving 0.6 Mt for domestic use, supplemented by minor imports.

The GHG emissions and removals of the forest sector in Finland are presented in Fig. 3. Total life cycle emissions, including emissions and removals from the Finnish production chain, imported raw materials, and the further processing of exported products abroad, were 8.35 Mt CO_2e.

Energy-related emissions (Scope 1 and 2) from the forestry sector were estimated at 3.01 Mt CO_2e, representing roughly 11% of Finland's total energy sector emissions (27.7 Mt CO_2e) as reported by Statistics Finland. These emissions primarily originated from forestry operations in Finland, domestic wood transport, and fuel and electricity combustion in the pulp and paper, sawn timber and wood panel industries.

The land use land use change and Forestry (LULUCF) component was a net carbon removal corresponding to a value of −0.38 Mt CO_2e. Emissions were mainly sourced from organic soils, and partly from mineral soils. Carbon removals were dominated by tree biomass growth (89%) followed by carbon stock changes in harvested wood products (11%).

Scope 3 emissions from domestic production were estimated at 2.46 Mt CO_2e, with 97% originating from upstream processes in pulp and paper manufacturing and the rest from sawmilling and panel industries. When combined with emissions from imported materials and export-related downstream processing, total scope 3 emissions were 6.64 Mt CO_2e. Emissions from domestic production were substantially lower compared to those assessed for import and export activities (63%). About 60% of the total emissions originated from export related processes, including transportation and further processing of exported items. Import activities contributed only 3%, primarily from transportation and forestry operations abroad. These results indicate the role of trade-related processes on the overall GHG emissions of the forestry sector in Finland. However, it is important to note that emissions arising from international trade is not reported in the Finland's official GHG inventory.

Fig. 4 illustrates the distribution of Scope 1, Scope 2 and Scope 3 emissions for the forestry sector in Finland. Scope 1 emissions and removals represented a substantial share of the total climate impact (i.e., total impacts from Sope 1, 2, and 3). However, their net contribution (i.e., around 2.22 $MtCO_2$e) was reduced due to the inclusion of sequestration credits, which offset a portion of the gross emissions. Within Scope 1, the largest contributor was organic soils, accounted for 13.95 $MtCO_2$e. Other notable sources included fuel use in pulp and paper production (1.37 $MtCO_2$e), forestry operations (0.61 $MtCO_2$e), domestic transport (0.58 $MtCO_2$e), and emissions from mineral soils (0.37 $MtCO_2$e). Scope 2 emissions, driven by electricity use, were dominated by pulp and paper production contributing 0.35 $MtCO_2$e, and followed by sawnwood and panel production to 0.05 $MtCO_2$e.

Scope 3 emissions, which encompass indirect emissions across the value chain, were considerably higher (5.73 $MtCO_2$e) than others and were largely linked to activities beyond the direct control of producers. Approximately 96% of scope 3 emissions originated from three major sources: upstream processes, transportation and further processing of exported goods. Among these, upstream emissions from pulp and paper production were 36% of the total scope 3 emissions, reflecting the energy-intensive nature of fuel production and raw material processing. For pulp production, chemicals such as sodium chlorate, sodium hydroxide, rosin soap and calcium oxide contributed about 75% of upstream emissions. In paper manufacturing, the key contributors included calcium carbonate, optical brightness and starches.

Export transportation accounted for 23%, driven by the Finland's strong export orientation and the long distances required to reach international markets. Finally, processing of exported goods abroad, primarily fibre-based products, accounted for 37% of scope 3 emissions, which was about equal to the contribution of upstream processes. Such distribution between scopes highlights the dominant role of supply chain emissions in the forestry sector's overall global warming impacts. While Scope 1 and Scope 2 emissions are relatively modest compared to national totals, the dominance of scope 3 emissions indicates that decarbonization strategies must extend beyond domestic operations. This can be possible, for example selecting low-emissions raw materials for domestic production.

The LULUCF impacts associated with imported wood used in Finland resulted in a net sequestration value of approximately −0.91 Mt CO_2e. This relatively high net removal is due to lower organic soil emission in most importing countries compared with Finland.

4. Discussion

This study quantified the life cycle greenhouse gas (GHG) emissions of Finland's forestry sector using a comprehensive approach that integrates both bottom-up analysis, based on chain-specific assessments of forestry operations and industrial processes, with top-down methods, which incorporate national statistics for land use land use change (LULUC) impacts for both Finnish and imported wood, as well as the sector's direct energy related emissions. This approach enables a holistic assessment of life cycle GHG emissions in Finland's forest sector by aligning with the Scope 1–3 structure, delineating the contributions of

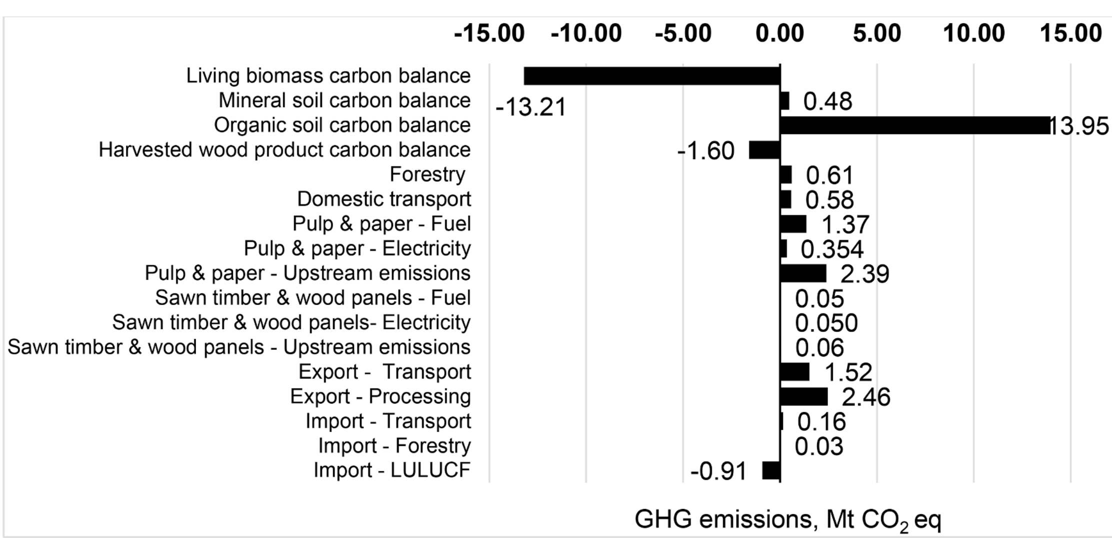

Fig. 3. Life cycle GHG emissions of Finnish forest sector.

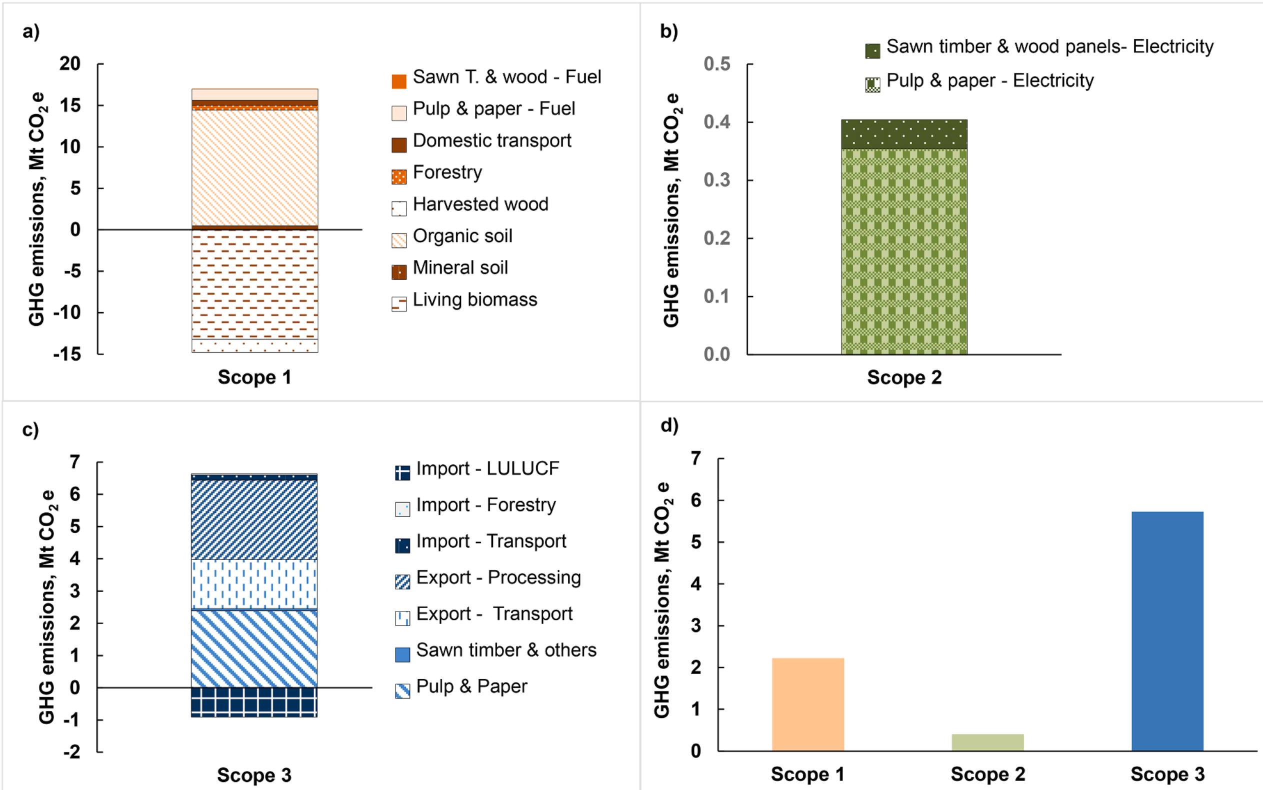

Fig. 4. Life cycle GHG emissions of the Finnish forestry sector in terms of Scope 1 (panel a), Scope 2 (panel b), and Scope 3 (panel c) with different scales in x-axis. Overview is shown in panel (d).

individual processes and materials, and defining clear system boundaries. Furthermore, the developed framework is designed to be flexible, allowing for annual updates and adaptation to other geographic contexts, thereby supporting broader applicability and continuous improvement.

The methodological choice is critical for the accurate calculation of emissions, whether for a single product or an entire sector. The use of a LCA approach enables the estimation of emissions for upstream, manufacturing, and downstream phases separately, thereby allowing comprehensive and detailed measurement of a product's total life cycle emissions. In a recent study, Karhinen et al. (2025) estimated the carbon footprint of exported products from Finland employing an input-output (I/O) approach based on emission factors originally developed by Seppälä et al. (2011). This approach calculates emissions in kg CO_2e per euro of economic value per year. For example, the emission factor for sawn timber was reported about 0.4 kg CO_2e per euro (Seppälä et al., 2011). Assuming a market price of 200 euros per cubic meter, this would correspond to emissions of 80 kg CO_2 per cubic meter. In contrast, our calculations estimate the emissions directly associated with sawn timber production as 9.68 kg CO_2e per cubic meter. This substantial discrepancy highlights the limitations of the input output approach in accurately characterizing greenhouse gas emissions in the bio-based sector, suggesting that LCA methodologies may provide more precise and sector-specific emission quantifications.

The greenhouse gas emissions attributed to forestry and logging activities in Finland are reported by Statistics Finland (2025b) as 0.365 Mt CO_2e, which is notably lower than the estimate presented in this study (0.608 Mt CO_2e). This discrepancy may be attributed to the exclusive life cycle inventory developed for forest management activities in this research, which provides a more comprehensive life cycle perspective than the scope captured in official statistics. Estimating emission factors at each stage of the production chain poses challenges due to data variability and system complexity. In this study, we addressed these challenges by first calculating emission factors for forestry activities, providing emissions values per cubic meter of harvested wood. Subsequently, emissions were estimated for each product-specific production process and logistic chain. For example, in the pulp production process, emissions were calculated solely for electricity, fuel, and materials inputs, primarily chemicals used within the pulp mill to isolate process-specific contribution.

The role of Scope 3 emissions is crucial, as they represent approximately 68% of total emissions. Addressing these emissions through improved materials and processes could help reduce overall emissions, along with other actions, such as practicing proper forest management that enhance carbon stock in forest ecosystems. Accordingly, accounting for LULUCF related sequestration is also very important. For instance, the tree biomass contributes to 13 Mt CO_2e of net sequestration in Scope 1 emissions. However, this sequestration is decreasing in Finland due to the aging of Finnish forests, and forest damage (Metsa Group, 2022; Pan et al. 2024; Silfver et al., 2024).

A comprehensive understanding of the life cycle emissions enables stakeholders to identify emission hotspots and make informed decisions to mitigate environmental impact. For example, decision-makers may opt for sustainable materials and processes or prioritize sourcing of low-impact raw materials. In Finland, energy related emissions are relatively low and approaching zero, leaving limited room for further emissions reductions. In contrast, emissions from organic soils remain very high, yet large-scale mitigation is not feasible in the short-term. Harvested wood products provide substantial potential for carbon removals by storing carbon in long-lived materials. This potential increases further when new technologies are used to produce value-added products and enhance material valorisation, particularly when combined with carbon capture and storage technologies. (e.g., Paltsev et al. 2021).

LCA is inherently data-intensive and requires detailed primary information from industries producing the final products to accurately quantify emissions at each process stage. Such data are often scarce or inaccessible due to confidentiality concerns within the industry. To bridge these data gaps, secondary sources such as published literature are frequently utilized. In this study, emission data for materials involved in the production of various paper products were sourced from the ecoinvent v3.11 database, while additional emission estimates, including fuel consumption in pulp and paper and solid wood production, were obtained from statistical databases. The dependence on secondary data may, however, reduce the precision and comprehensiveness of emission assessments for the forestry sector. Therefore, future efforts should focus on updating emission datasets and models, particularly global value-chain inventories and country-specific export logistics as well as material production process to better reflect the forestry sector's true life cycle emissions.

Framework for developing bioeconomy databases is still relatively new, and comparable literature or reference databases for validation of the results remain limited. For the life cycle inventory data applied in this study, the general quality criteria were followed, and data with the best possible geographical and temporary representativeness were selected for the assessment. Our approach also relies on national statistical sources, which can have uncertainties that are not easy to quantify. A key limitation and substantial uncertainty concern is related to the LULUCF carbon balance, as observed by Kangas et al. (2026). This uncertainty arises primarily from limitations in models for biomass growth and peatland soil emissions. Similar uncertainties concern also the LULUCF emissions and removals of imported wood, especially because different countries use different methods for their LULUCF inventories, and therefore the results are not fully comparable. This uncertainty is one reason why the authors of the Kangas et al. (2026) report suggest treating LULUCF as a separate component within the national GHG accounting and climate policy. The framework presented in this study allows such a separation, makes it possible to handle the forest sector LULUCF emissions and removals as an individual entity, and therefore provides better opportunities to set relevant and more precise climate changes mitigation targets for different sectors.

5. Conclusion

This study provides a comprehensive life cycle GHG emissions and removal assessment of the Finnish forest sector. The methodology developed in this work broadens the scope of emissions assessment from a product-specific perspective to GHG emissions and removal from the entire life cycle of wood and fiber flows processed in the Finnish forest sector. Its flexible design enables annual updates and adaptation to different geographic regions, offering a novel approach to quantifying the climate impact of forestry activities. By incorporating emissions from Scope 1, Scope 2, and Scope 3, and accounting for import, export, and LULUCF, the approach provides a detailed understanding of the sector's total induced GHG emissions.

Overall, the results highlight the importance of considering a life cycle perspective to identify the contributions of emissions and removals from different products, materials, energy sources, scope levels, etc. For instance, the assessment for 2023 reveals a total life cycle GHG emissions of approximately 8.35 Mt CO_2e. When emissions and removals associated with LULUCF are excluded, the figure increases to around 9.64 Mt CO_2e. Further exclusion of emissions linked to wood trade reduces the estimate to 5.08 Mt CO_2e, while excluding Scope 3 emissions yields an approximate total of 2.63 Mt CO_2e. Organic soils are the largest contributors to the life cycle GHG emissions of the Finnish forest sector, followed by export transport within Finland, export processing, and paper materials. Most of the total emissions originate from Scope 3 sources, followed by Scope 1 emissions, while Scope 2 emissions are negligible. LULUCF in Finland results in a net sequestration, corresponding to a value of around −0.38 Mt CO_2e and imported wood contributes to carbon sequestration of approximately −0.95 Mt CO_2e. These results underscore the significant contributions of LULUCF, particularly organic soil emissions, and international trade activities to the overall emissions profile of the Finnish forestry sector, emphasizing the necessity of a life cycle perspective for accurate emission accounting and the development of effective mitigation strategies.

This comprehensive assessment enables a better understanding of the emission profile and helps plan emission reduction strategies without shifting the emission problem elsewhere or simply focusing on reducing volume.

CRediT authorship contribution statement

Ashraful Alam: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Hafiz Usman Ghani:** Writing – review & editing, Writing – original draft, Methodology. **Tarmo Räty:** Writing – review & editing, Supervision, Methodology, Investigation. **Ilkka Leinonen:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

Authors have nothing to declare, except from the funding acquired for the project in which the study of the manuscript was done.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcradv.2026.200366.

Data availability

Data will be made available on request.

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