



Land use and land use change emissions of forest land in Finnish provinces—an LCA dataset

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Abstract

Purpose The land use and land use change (LULUC) emissions and removals are an important part of the carbon footprinting of forest products with the life cycle assessment (LCA). For example, in Finland, forests are an important—though reducing—carbon sink, which is not typically visible in global warming potential (GWP) of forest products. To improve the accuracy of forest LCA, a province-level dataset was combined for specific Finnish provinces following a top-down approach.

Methods The dataset of GWP_{LULUC} was created from Finnish forest statistics data from 2015 to 2021. A total of eight provinces from the northern and eastern Finland were included. The carbon pools in the dataset included living biomass (trees), mineral soils and drained organic soils. As a case study, the dataset values were applied for m^3 and tonne C of harvested wood biomass of Norwegian Spruce, as well as 1 l of bioethanol production and 1 l of E20 (20% blend of bioethanol with petrol) vehicle use.

Results and discussion GWP_{LULUC} values varied between the studied provinces, from net negative to net positive. The variation was mostly attributed to living biomass carbon stock, followed by areas of drained organic soils in different provinces. Overall, GWP_{LULUC} showed an increasing trend in 2015–2021. When GWP_{LULUC} was added to the GWP of harvested wood biomass, it dominated and led to net negative GWPs in half the studied provinces. Yet, if GWP_{LULUC} emissions continue increasing, the currently net negative GWPs may approach zero and even become net positive. The contribution of GWP_{LULUC} was also high for bioethanol production and varied between the studied provinces.

Conclusions The created dataset will help improving the accuracy of Finnish forest LCA assessments and will be especially important for comparisons between fossil and bio-based products. The findings of the case studies highlight the importance of using province-level data in forest LCA whenever they are not limited by traceability and data availability.

Keywords Life cycle assessment · GHG emissions · Soil carbon · Forest land · Global warming potential · CO₂ removals

1 Introduction

Forests are an important storage of carbon globally, storing carbon in both biomass and soil. To mitigate climate change, it would be beneficial to increase the carbon stock of forests and thus remove CO₂ from the atmosphere. For example, this can be achieved through afforestation or reforestation of

improved forest management (IPCC 2021). Possible carbon removal of forests should also be considered at the product level and included in the carbon footprint of forestry products (ISO 2018). In Finland, forest land covers 86% of the land area (Korhonen et al. 2017). The management of Finnish forests has improved their carbon sequestration, and for decades, forests have sequestered more carbon than they have lost, which has made them a carbon sink (Statistics Finland 2023). However, the carbon sink of Finnish forests has reduced since the 1990s leading to net emissions of the whole land use, land use change, and forestry (LULUCF) sector of the National Greenhouse Gas (GHG) Inventory (Statistics Finland 2023). The continuous trend in the reduction of the forest carbon sink is related to reduced growth rate and increased tree mortality of ageing forests, as well as increased GHG emission from drained organic soils as

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a result of climate warming. The year-on-year variation in the carbon sink is also related to annual harvest rates (Luke 2024a).

Land use and land use change (LULUC) emissions and removals are known to have a major impact on the global warming potential (GWP) of forestry products, and they may occasionally lead to the carbon negativeness of forest products (Røyne et al. 2016). Yet, the LULUC emissions and removals of forest land have been often excluded from carbon footprinting conducted with the life cycle assessment (LCA). The exclusion of LULUC emissions from LCA is against guidelines such as PAS2050:2011 (BSI 2011), the Product Environmental Footprint (PEF) guidelines (European Commission 2021), and the ISO 14067 standard (ISO 2018). If included in the attributional LCA of forestry, LULUC emissions and removals have often been included at country level following methods such as PAS2050:2011 (BSI 2011) or IPCC Tier 1 (IPCC 2006b). The country level provides average estimates and is useful in cases when more precise data are unavailable, or the origin of the forest-based material is not known in detail. However, the LULUC impacts can potentially vary depending on the local climate and soil characteristics as well as forest management. The inclusion of LULUC emissions and removals in the GWP of forest products is important, especially in cases where the GWPs of bio-based and fossil materials or energy sources are compared. The same also applies to other applications of LCA, including company GHG inventories and the provision of holistic information to policymakers via life cycle thinking.

The study aimed to create a forest land GWP_{LULUC} life cycle inventory dataset for specific provinces in Finland. This was to improve the accuracy of the GWP of Finnish forestry products. GWP_{LULUC} is affected by the spatial scale, and a geographically resolved approach is therefore more relevant for capturing the regional perspective (EPA 2011). The created dataset was applied for a case study of the GWP of harvested wood biomass and bioethanol to estimate the effect of province-to-province variation on product GWP.

2 Methods

2.1 Provinces

The provinces included in the dataset were in northern and eastern Finland (Fig. 1). These provinces have significant forest land areas, totalling 53% of forest land in Finland (Table 1). The annual roundwood harvests in these provinces account for a total of 53% of roundwood harvests in Finland. North Savo, North Ostrobothnia, North Karelia, and South Savo especially have significant annual roundwood harvest quantities. The area of drained organic soils varies between

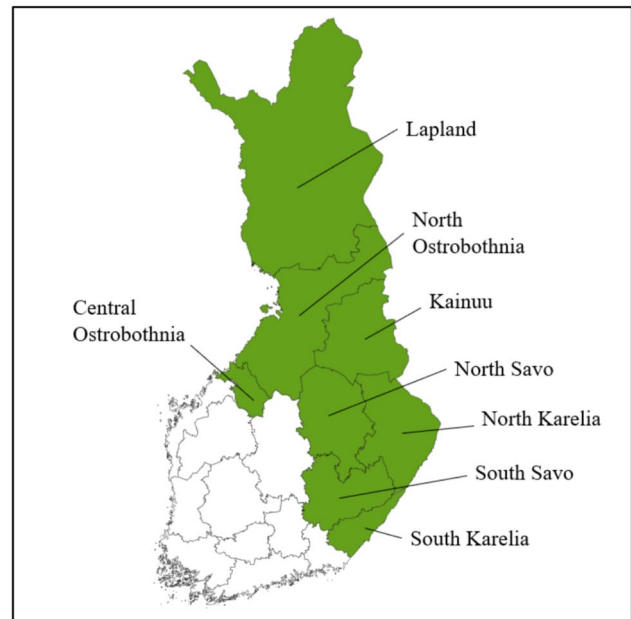


Fig. 1 The provinces of Finland included in the assessment

the provinces from 15 to 44% of the total forest land, being highest in Central and North Ostrobothnia.

2.2 Carbon stock change calculations

The method used to create the data is described in more detail by Lehtilä et al. (2025). The LULUC-related land carbon stock changes (ΔC_{LULUC}) estimated with the method represented annual changes in land carbon stocks, including living biomass, mineral soils, and organic soils. The negative ΔC values correspond to net carbon removals from the atmosphere (i.e. LULUC removals), while positive ΔC values correspond to net carbon emissions to the atmosphere (i.e. LULUC emissions).

In principle, ΔC_{LULUC} consists of land carbon stock changes on (i) forest land remaining forest land and (ii) land converted to forest land, that is, land that has been converted to forest land within the last 20 years before the assessment year (IPCC 2006b). The main drivers for ΔC_{LULUC} are land management of forest land remaining forest land and land use changes on land converted to forest land. Here, we focus only on the land carbon stock changes on *forest land remaining forest land*, to assess the impacts of land management on the carbon stock changes at province level. That was decided because of the current data availability at Finnish province level, as well as the marginal contribution of land use change-related carbon stock changes of the average GWP_{LULUC} of Finnish forest land (<3% of total GWP_{LULUC} ; Lehtilä et al. 2025).

Table 1 Forest land characteristic of the provinces included in the dataset

| | Forest land area (1000 ha)* | Share of total forest land in Finland located in the province (%) | Roundwood harvests (1000 m ³ /year)** | Roundwood harvests (% of harvested in whole Finland) | Drained organic soil area out of total forest land area (%)*** |
|----------------------|-----------------------------|---|--|--|--|
| South Karelia | 414 | 2 | 2483 | 3 | 16 |
| South Savo | 1061 | 4 | 6394 | 8 | 16 |
| North Savo | 1370 | 5 | 7678 | 10 | 21 |
| North Karelia | 1561 | 6 | 6959 | 9 | 26 |
| Central Ostrobothnia | 337 | 1 | 1061 | 1 | 43 |
| North Ostrobothnia | 2544 | 10 | 7682 | 10 | 44 |
| Kainuu | 1625 | 6 | 3809 | 5 | 33 |
| Lapland | 4920 | 19 | 4915 | 6 | 15 |

*Luke (2024b), data from 2021; **Luke (2024a), data from 2021; ***Luke (2024c), data from National Forest Inventory 12/13 (2018–2022)

As mentioned above, the estimated ΔC_{LULUC} (kg CO₂/ha) included carbon stock changes in living biomass (ΔC_{LB}), mineral soil ($\Delta C_{SOC,min}$), and organic soil ($\Delta C_{SOC,org}$). The data for the specific ΔC values in different provinces were derived from the Kärkkäinen et al. (2023) dataset, also available as online statistics (Luke 2024d). Data from 2015–2021 were included in the dataset. Kärkkäinen et al. (2023) employed forest area, tree volume, and tree growth data from the National Forest Inventory 2017–2021 (Korhonen et al. 2017, 2021) and used the carbon balance calculation methods of the National GHG Inventory of Finland (Statistics Finland 2023). In this National GHG Inventory, the carbon balance of living biomass (i.e., above and belowground biomass of trees) is calculated by the IPCC (2006b) Tier 3 gain–loss method, while the carbon balance of mineral soils is calculated by utilising the Tier 3 Yasso07 model (Tuomi et al. 2009). In Kärkkäinen et al.’s (2023) dataset, the CO₂ emissions of drained organic soils are specified using a method by Alm et al. (2023).

The total land ΔC_{LULUC} per m³ was calculated as follows:

$$\Delta C_{LULUC} = \frac{(\Delta C_{LB} + (\Delta C_{SOC,min} \times A_{min}) + (\Delta C_{SOC,org} \times A_{org}))}{Harvested\ biomass} \quad (1)$$

where.

ΔC_{LULUC} = Annual land carbon stock change on forest land (kg CO₂/m³).

ΔC_{LB} = Carbon stock change in living biomass (kg CO₂/ha/yr) (note: only tree biomass accounted for).

$\Delta C_{SOC,min}$ = Carbon stock change in mineral soil carbon stock (kg CO₂/ha/yr).

A_{min} = Share of mineral soils of the total forest land within the province (dimensionless).

$\Delta C_{SOC,org}$ = Carbon stock change in drained organic soil carbon stock (kg CO₂/ha/yr).

A_{org} = Share of drained organic soils of the total forest land within the province (dimensionless).

Harvested biomass = total annual roundwood harvest per hectare of forest land in the province (m³/ha/yr). Derived for the different provinces from Finnish statistics (Luke 2024a).

The N₂O and CH₄ emissions of drained organic soils in different provinces were calculated by utilising emission factors (0.92 kg N₂O-N/ha/year and 6.42 kg CH₄/ha/year) derived from the National GHG Inventory (Statistics Finland 2023). The emission factors were originally based on IPCC (2014) emission factors and weighted by the average area of nutrient-rich and nutrient-poor organic soils of Finnish forest land.

The total N₂O and CH₄ emissions from drained organic soils per m³ were calculated as follows:

$$N2O_{org} = \frac{(EF_{N2O} \times 273) \times A_{org}}{Harvested\ biomass} \quad (2)$$

$$CH4_{org} = \frac{(EF_{CH4} \times 29.8) \times A_{org}}{Harvested\ biomass} \quad (3)$$

where.

$N2O_{org}$ = N₂O emissions of drained organic soils (kg CO₂ eq./m³).

EF_{N2O} = N₂O emissions factor for forest land (kg N₂O/ha/yr).

273 = factor to convert N₂O into CO₂ equivalents (IPCC 2021).

$CH4_{org}$ = CH₄ emissions of drained organic soils (kg CO₂ eq./m³).

EF_{CH4} = CH₄ emissions factor for forest land (kg CH₄/ha).

29.8 = factor to convert CH₄ into CO₂ equivalents (IPCC 2021)

A_{org} = Share of drained organic soils out of the total forest land (dimensionless).

Harvested biomass = total annual roundwood harvest (m³/ha/yr).

Note that although both N_2O_{org} and CH_4_{org} are related to LULUC, only CH_4_{org} is further included under category GWP_{LULUC} , while N_2O_{org} is included under GWP_{fossil} . This is due to the categorisation presented in the PEF guidelines (European Commission 2021), according to which GWP_{LULUC} consists of carbon-including gases.

The dataset including the total GWP_{LULUC} ($= \Delta C_{LULUC} + CH_4_{org}$) and N_2O_{org} values used in the calculations are presented in Supplementary Material.

2.3 GWP calculations

The province-level dataset of land carbon stock changes was demonstrated by calculating the GWP of harvested wood biomass in the studied provinces. The system boundary of the case study extended from forest plantation to silvicultural operations and the harvest of the forest site. GWP was calculated per functional unit (FU) of 1 m³ of harvested wood biomass. Additionally, the results were presented per tonne (1000 kg) of carbon in harvested wood biomass. The factor used to convert m³ into kg was 380 kg/m³, representing the harvested wood biomass of Norwegian Spruce (Niinistö et al. 2023).

GWP was divided into three parts, to align with the European Commission (2021) recommendation:

- i) GWP_{fossil} = fossil GHG emissions, including also all N_2O emissions;
- ii) $GWP_{biogenic}$ = biogenic GHG emissions (i.e., GHGs including carbon) other than GWP_{LULUC} ;
- iii) GWP_{LULUC} = GHG emissions related to LULUC (note: here only the impacts of land management, see a further description in Sect. 2.2).

The same GWP_{fossil} from fuel consumption in silvicultural operations per m³ was included for all provinces. This data were derived from ecoinvent (v. 3.10), representing the softwood production of Norwegian Spruce. The N_2O emissions from peat oxidation in drained organic soils (N_2O_{org}) in different provinces were included in GWP_{fossil} , as only CO_2 and CH_4 were included in the GWP_{LULUC} category (European Commission 2021; Lehtilä et al. 2025).

$GWP_{biogenic}$ was assumed to be zero, as the 0/0 approach (BSI 2011; European Commission 2021) was followed and the potential carbon storage in harvested wood biomass was excluded from the assessment. This was decided because the system boundary did not include product use or end-of-life phases, and the product carbon storage is typically less than 100 years and therefore considered to be as short term.

The GWP_{LULUC} was calculated as a sum of ΔC_{LULUC} and CH_4_{org} , separately for each province (European Commission 2021; Lehtilä et al. 2025). Here, GWP_{LULUC} calculations were performed for the harvested wood biomass

in 2021 in eight different provinces in Finland. Additionally, an analysis of annual variability in 2015–2021 was performed.

Furthermore, to demonstrate the applications of GWP_{LULUC} at the product level, GWP calculations including GWP_{LULUC} were also performed for forest-based bioethanol production and use across the studied Finnish provinces. The system boundary was considered from cradle to grave, including the spruce wood chips as raw material, transport, bioethanol production, blending with petrol, and vehicle use. We considered E20 fuel as a 20% blend of bioethanol with 80% of petrol by volume. The functional units were defined as 1 l of bioethanol production and 1 l of E20 use in the vehicle. For GWP_{fossil} and $GWP_{biogenic}$, ethanol and petrol production data were sourced from ecoinvent (v. 3.10), and the emission factors for E20 and petrol use are obtained from the European Environment Agency (EMEP/EEA 2019). Bioethanol is part of harvested carbon, so GWP_{LULUC} was allocated to bioethanol based on its carbon content (0.52 kg C/l). The density of wood chips was considered to be 430 kg dry weight/m³ (UNECE 2010), and the carbon content of biomass was considered to be 50% of the dry matter content (IPCC 2006a).

3 Results

The net GWP_{LULUC} of forest land was highest in North Ostrobothnia (297 kg CO_2 eq./m³), and net emissions also occurred in South Karelia (185 kg CO_2 eq./m³), South Savo (174 kg CO_2 eq./m³), and North Savo (78 kg CO_2 eq./m³) (Fig. 2). In North Ostrobothnia, carbon removals in living biomass and mineral soils were exceeded by organic soil emissions. In South Karelia and South Savo, both living biomass and organic soils caused net carbon emissions. GWP_{LULUC} was most clearly negative in Lapland (−1882 kg CO_2 eq./m³), leading to the highest net carbon removals from the atmosphere (Fig. 2). Net carbon removals were also recorded in Kainuu (−336 kg CO_2 eq./m³), Central Ostrobothnia (−207 kg CO_2 eq./m³), and North Karelia (−79 kg CO_2 eq./m³). The carbon removals were mainly related to the carbon stock increases in living biomass due to the increasing growth of Finnish forests, which compensated for the organic soil carbon stock losses. Only in Lapland, the organic soils were net sinks of carbon. In all provinces, mineral soils were net carbon sinks (Fig. 2).

Per tonne of C in harvested wood biomass, the maximal net removals of GWP_{LULUC} were 675 kg C in Lapland (Table 2). In other provinces, the removals of GWP_{LULUC} were 28–120 kg C, while the emissions of GWP_{LULUC} were 28–106 kg C per tonne of C in harvested wood biomass.

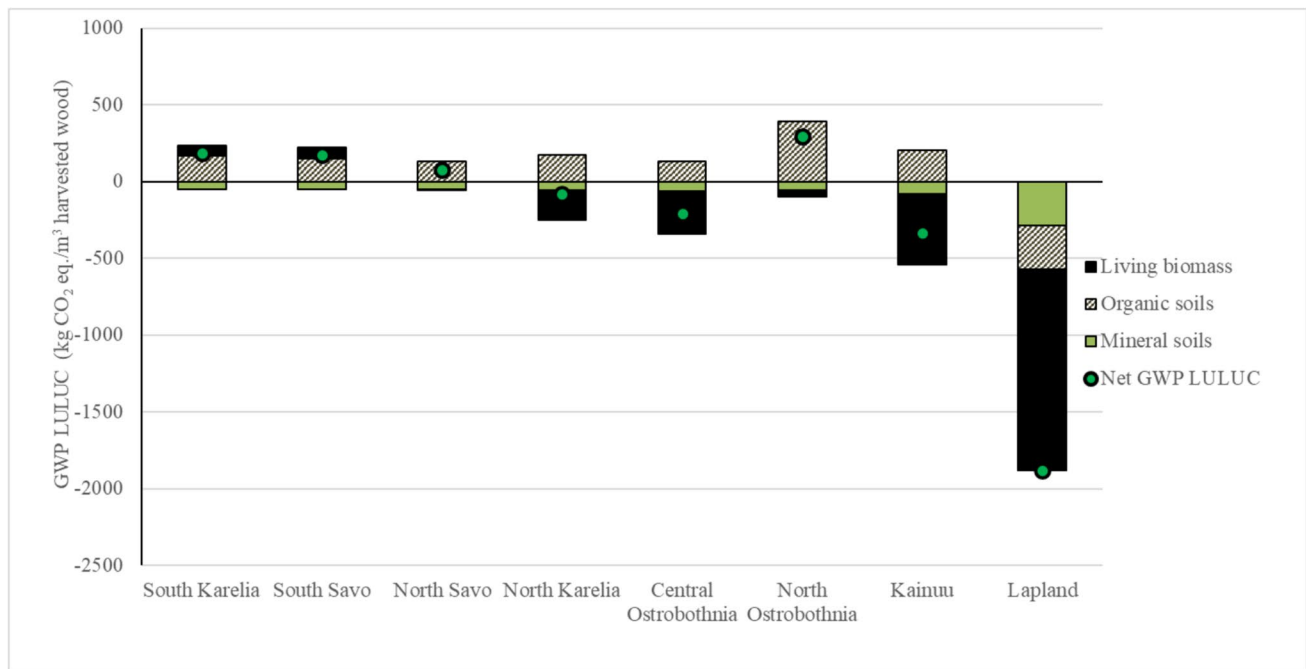


Fig. 2 Forest land GWP_{LULUC} caused by the changes in different carbon stocks (living biomass, mineral soil, and drained organic soils) in eight different Finnish provinces. The points show the net

GWP_{LULUC} , and the bars show the contributions of different carbon stocks to GWP_{LULUC} . The values represent 2021

Table 2 Forest land GWP_{LULUC} in eight different Finnish provinces, presented per tonne of C in harvested wood biomass of Norwegian Spruce. The values represent 2021 are presented and edited correctly; otherwise, kindly amend

| Province | GWP_{LULUC} | |
|----------------------|--|---|
| | kg CO ₂ eq./tonne C in harvested wood biomass | kg CO ₂ -C eq./tonne C in harvested wood biomass |
| South Karelia | 244 | 66 |
| South Savo | 228 | 62 |
| North Karelia | 103 | 28 |
| North Savo | -104 | -28 |
| Central Ostrobothnia | -273 | -74 |
| North Ostrobothnia | 391 | 106 |
| Kainuu | -442 | -120 |
| Lapland | -2476 | -675 |

Overall, the average GWP_{LULUC} of all studied provinces was negative, although it approached zero in 2015–2021 (Fig. 3). The increasing trend of LULUC emissions occurred in all studied provinces except for South Karelia and South Savo. The annual variability of GWP_{LULUC} was highest in North Karelia, North Ostrobothnia, and Lapland.

When included in the total GWP of harvested wood biomass, GWP_{LULUC} showed a high contribution, as GWP_{fossil}

remained marginal in all studied provinces (Fig. 4). Net GWP was positive—meaning net emissions—in North Ostrobothnia (367 kg CO₂ eq./m³), South Karelia (204 kg CO₂ eq./m³), South Savo (192 kg CO₂ eq./m³ harvested wood biomass), and North Savo (101 kg CO₂ eq./m³). In the rest of the studied provinces, the production of wood biomass caused net removals of carbon from the atmosphere. The net removal was highest in Lapland (-1813 kg CO₂ eq./m³), where GWP_{LULUC} was 27-fold compared to GWP_{fossil} .

The highest GWPs of bioethanol production were recorded for North Ostrobothnia (1.37 kg CO₂ eq./l), South Karelia (1.05 kg CO₂ eq./l), and South Savo (1.02 kg CO₂ eq./l) (Fig. 5). In those provinces, GWP_{LULUC} covered 30–40% of total GWP, while the rest was attributed to GWP_{fossil} . In North Karelia, Central Ostrobothnia, and Kainuu, GWP_{LULUC} was negative, but net GWP was still positive due to GWP_{fossil} . In Lapland, the GWP of bioethanol production was lowest, with net GWP of -2.81 kg CO₂ eq./l.

GWP of E20 (20% of bioethanol and 80% petrol) consumption was 10–37% lower than petrol, depending on the province (Fig. 6). GWP was lowest for E20 including bioethanol made from forest biomass from Lapland (1.99 kg CO₂ eq./l), while it was highest for Kainuu (2.58 kg CO₂ eq./l). Overall, the contribution of GWP_{LULUC} to the total GWP of E20 varied from -36% to +4%, and it remained marginal (< +/- 5%) for all provinces except for Lapland.

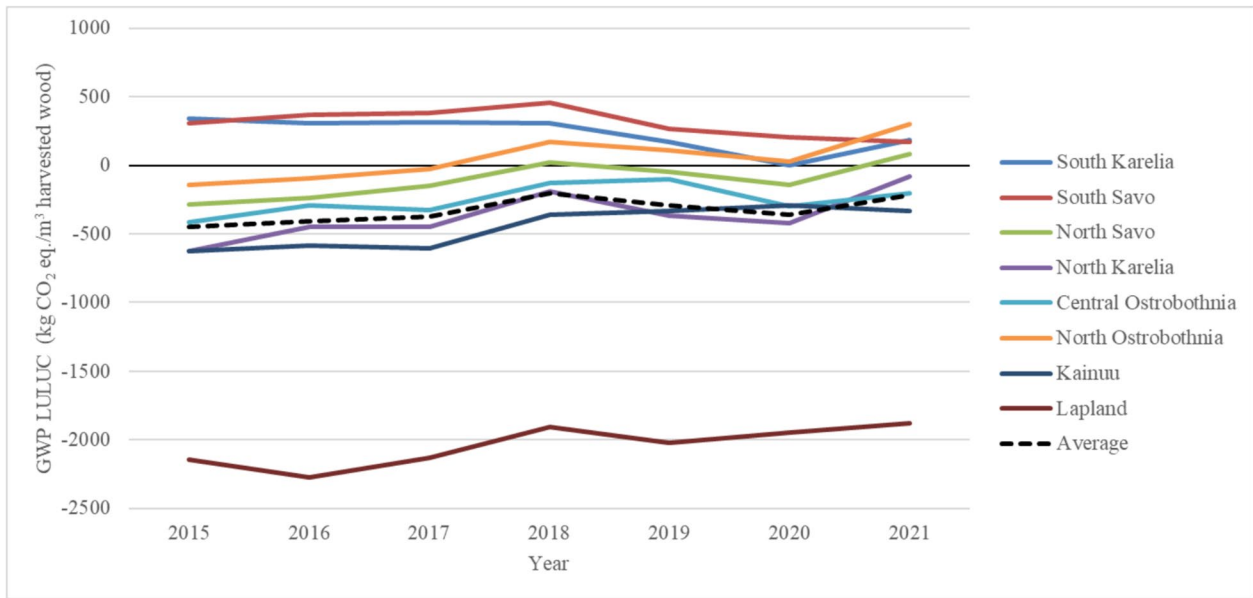


Fig. 3 The annual variability of forest land GWP_{LULUC} in eight different provinces of Finland in 2015–2021

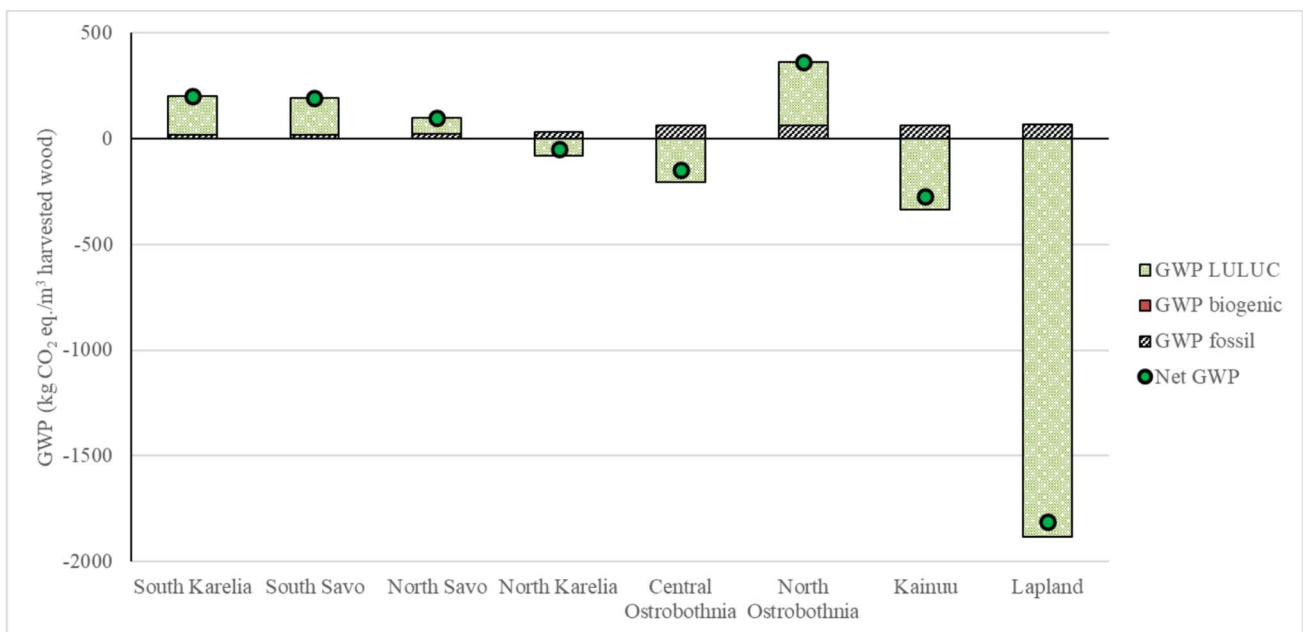


Fig. 4 GWP of harvested wood biomass (from cradle to gate) in eight different Finnish provinces. The points show net GWP, and the bars show the contributions of three different GWP categories. The values represent 2021

4 Discussion

Overall, in all studied provinces, the living biomass carbon sink showed a decreasing trend in 2015–2021. There are two main reasons for this. First, there is increased removal of forest biomass, related to the fact that annual harvest rates have increased in throughout Finland (Statistics

Finland 2023), and the natural mortality of trees has also increased (Luke 2024e). Increased harvests have led to a reduced carbon sink in living biomass. Second, the growth rate of the forests is continuously slowing down. This is related to the age structure of the forests. Many of the current forests were planted during the 1950s and 1960s and the fast growth of young forests from the 1970s onwards

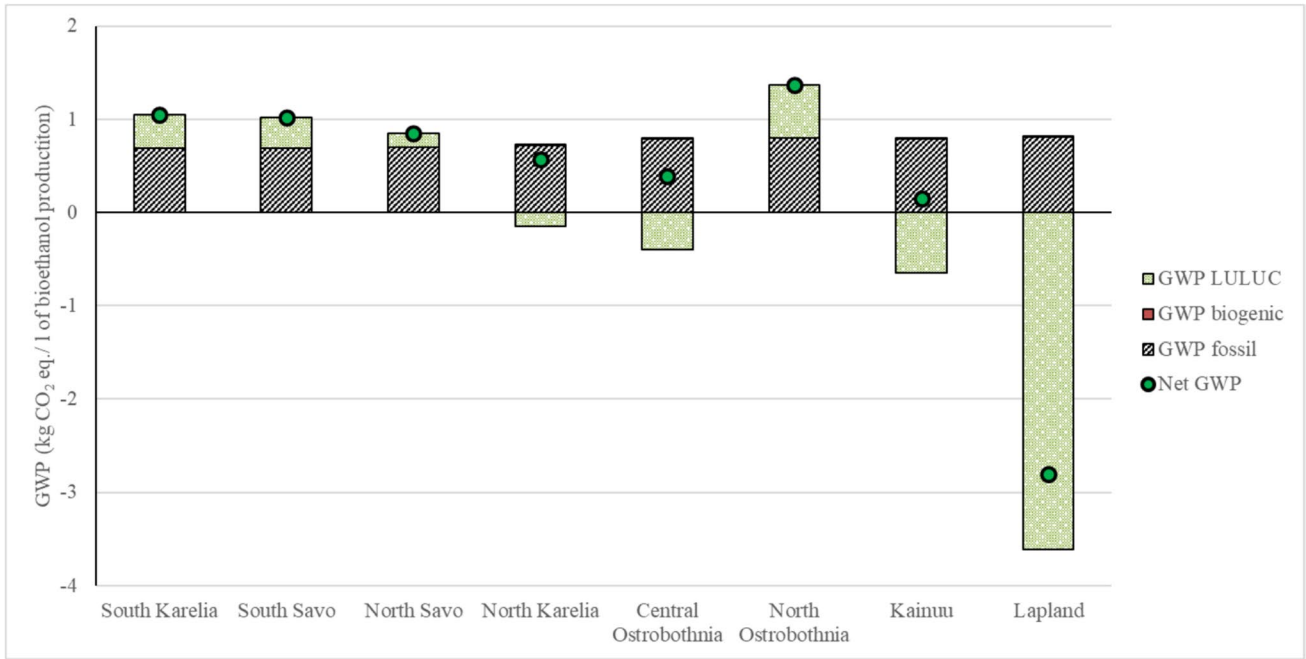


Fig. 5 GWP of 1 l of bioethanol production (from cradle to factory gate), separately for eight different Finnish provinces. The points show net GWP, and the bars show the contributions of three different GWP categories

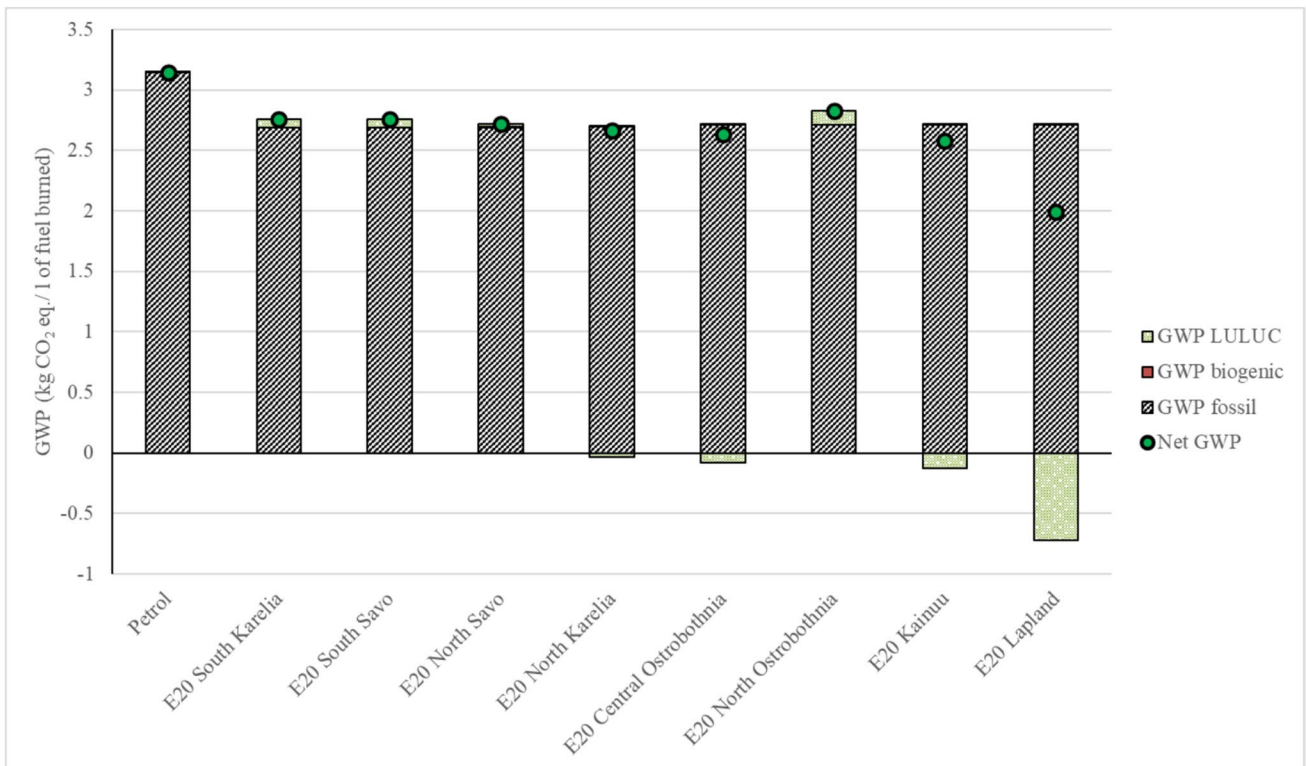


Fig. 6 GWP of 1 l of burned petrol and E20 (from cradle to grave). The E20 consists of 80% petrol and 20% bioethanol from different Finnish provinces. The points show net GWP, and the bars show the contributions of three different GWP categories

created the strong carbon sink of Finnish forests. However, now the forests have passed the phase of their fastest growth (Mehtätalo et al. 2025), and the growth rate is continuously decreasing. This is expected to further reduce the forest carbon sink in the near future.

If harvest rates continue to increase in the future, the carbon sink of living biomass may reduce or become a net source of carbon emissions. Even if harvest rates reduced, the same result would happen because of forest ageing, which slows down tree growth and increases natural mortality. However, climate warming may have increased tree biomass growth, yet it probably increases soil organic matter decomposition and thus carbon stock losses, especially in organic soils (Sievänen et al. 2014). Other factors related to climate change, such as increased droughts and outbreaks of damage caused by insects, may further reduce forest growth. GWPs of harvested wood biomass and bioethanol that are now net negative in some provinces may therefore diminish or even reverse, becoming a future net source of carbon emissions. Hence, steps should be taken to ensure sustainable harvesting at the provincial level to prevent overharvesting, along with efforts to enhance biomass growth by following management practices (e.g. reduced thinning and longer rotation cycles for forest stands; Haakana et al. 2022; Ghani et al. 2025). The better availability of data, as developed for the eight provinces in this study, could help to influence wood procurement from areas with carbon sinks and improve forest carbon sequestration.

The differences in GWP_{LULUC} between the provinces were distinct. When included in the total GWP of harvested wood biomass, the effect of GWP_{LULUC} was dominant, similar to the study by Michelsen et al. (2012). Moreover, the GWP of bioethanol production ranged from net negative to net positive depending on the quantity of GWP_{LULUC} emissions. Within GWP_{LULUC} , carbon stock changes in living biomass were especially highly variable within the studied provinces. In this assessment, losses in living biomass carbon stock were observed in the most southern provinces of the assessment, South Savo and South Karelia. The underlying reason is related to the fact that in southern Finnish forests, harvest levels and natural mortality have exceeded the growth that has reduced as a result of ageing, while in northern Finland, harvest levels and natural mortality have remained lower than growth. Differences in the drained organic soil area in the studied provinces were also visible in GWP_{LULUC} results. Organic soil emissions were highest in North Ostrobothnia, where drained organic soils account for 44% of forest land (Luke 2024c). Generally, drained organic soils were a net source of emissions in all provinces except Lapland, because of its cool temperatures restricting peat decomposition compared to provinces farther south. Overall, drained organic soil emissions in the

studied provinces increased in 2015–2021, following climate warming that increases peat decomposition (Sievänen et al. 2014; Statistics Finland 2023).

The clear impact of GWP_{LULUC} in the net GWP of harvested wood biomass and bioethanol highlights the need to use province-level data in LCA instead of country-level or other low-resolution data. However, this is possible only if province-level data are available and if the products can be traced to the province level. When using province-level data, the GWP of forestry products can be specified to represent the province's climate and soil conditions as well as harvest rates. It is important to include the variation of drained organic soil areas in different provinces in LCA to create incentives to reduce organic soil emissions via reduced tree harvest rates, for example (Mäkelä et al. 2023). It is also important to consider varying harvest rates in LCA, as harvest rates ($m^3/1000 \text{ ha/yr}$) in Finland vary greatly between the provinces, for example. Because of the effects on the living biomass and soil carbon stock dynamics, harvest rates have a high impact on forestry LCA results. The harvest rate also has a direct influence on LCA results if a volume-based FU is used. For example, in principle, if the GHG emissions related to forest production remain the same per 1 ha, but the harvest rate per ha increases by a third, the GWP of 1 m^3 harvested wood biomass decreases by 25%.

The presented dataset of this assessment represents a top-down approach that evaluates average province-level annual harvests and forest land carbon stock changes. The dataset can be used in attributional LCA assessments. In future, the dataset may be supplemented by updating forestry data from Finnish provinces, as harvest rates especially fluctuate annually. The dataset may be reproduced for different geographical areas if province-level forestry data are available. However, the dataset is not optimal for site-level assessments (bottom-up approach), where the effects of climate and soil conditions, as well as forest management and disturbances (e.g. pests and fires) can be assessed in more detail. To create such an LCA method for Finland, empirical and modelling data representing the local conditions and management should be aggregated to improve the representativeness of GWP_{LULUC} .

The main source of uncertainty in the results was related to the underlying ΔC data used, which are produced by considering specific forest stands and methodological choices. For example, the location and therefore the climate and soil conditions as well as the management of a specific forest stand from which the wood is sourced can differ from the average values. In addition, the province-specific data used were valid only for forest land remaining forestland, without specific consideration of land converted to forest land within the last 20 years before the assessment, that is, land use change-effects. Furthermore, the evaluation of GWP_{LULUC} also introduced uncertainties due to the

employed characterisation factors. However, uncertainty calculations were not performed due to challenges associated with the large dataset and missing data.

5 Conclusions

In this assessment, a GWP_{LULUC} dataset was created for forest products from eight Finnish provinces. The dataset was based on a top-down approach and aimed to improve the accuracy of LCA via consideration of province-specific characteristics. The dataset was demonstrated with case studies for harvested wood biomass of Norwegian Spruce, as well as bioethanol and E20 fuel (20% blend of bioethanol with petrol). The results showed high variance in GWP_{LULUC} between the studied provinces, merely related to differences in harvest rates and shares of drained organic soils. Although GWP_{LULUC} averaged over the provinces was negative, it increased in 2015–2021. If the increasing trend of LULUC emissions continues, forest land may shift from being a net carbon sink (negative GWP_{LULUC}) to a source of carbon emissions (positive GWP_{LULUC}), thus increasing the total GWP of forest products. In this assessment, the importance of considering the province-to-province differences was suggested, granted that the origins of forest products can be traced and the province-level information about the forest land carbon balances and harvest rates is available. In future, the dataset may be used in attributional LCA for Finnish forest products with regular data updates, and it could be reproduced for other countries.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-025-02456-5>.

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Data availability Data used in the publication are either public or available on request from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

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