



Evaluating the global warming potential of harvested wood due to the carbon stock changes under different forest management practices

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ABSTRACT

The European forests are essential in achieving the land use and land-use change (LULUC) related CO₂ removal targets. Adoption of various harvesting practices significantly influences the overall LULUC emissions and removals of forests. In this study, we used the life cycle assessment (LCA) approach to systematically evaluate the land use and land use change-related emissions and removals (GWP_{LULUC}) of harvested wood raw material. We applied different case study scenarios with different forest management practices in Finland in comparison to the business as usual scenario (one pre-commercial thinning and two commercial thinnings): i) a scenario with no pre-commercial thinning, ii) a scenario with reduced thinning with longer rotation cycle, and iii) a scenario with collection of logging residues. We also explored the effect of management on land occupation. We modeled various scenarios using the MOTTI stand simulation for birch, spruce, and pine, encompassing different vegetation types across various regions of Finland. This was followed by soil carbon modelling using the Yasso07 model to assess the effect of residue collection for spruce. Our analysis indicated that the management effects on GWP_{LULUC} emissions and removals vary across regions, vegetation types, and management practices. Especially, reduced thinning with longer rotation cycles results in significant carbon removals and lowest land occupation due to the longest rotation cycle (except for birch). The collection of residues leads to small losses of soil organic carbon, but the effect was a negligible factor in the overall GWP of wood raw material. These findings underscore the intricate interplay between regional, species-specific, and management-related factors in shaping the GWP_{LULUC} of forest-based products.

1. Introduction

Forests play an important role in maintaining the balance of GHGs in atmosphere (GWP; IPCC, 2021; Maierhofer et al., 2024) and remove approximately one-fourth of the global anthropogenic CO₂ emissions by increasing the carbon stock (Friedlingstein et al., 2023). The European Union (EU) has set a net GHG removal target of 310 million tonnes of CO₂ eq. by 2030, corresponding to the land use, land-use change, and forestry (LULUCF) sector's global warming potential (GWP_{LULUC}),

representing a 15 % increase compared to the current removal levels (European Parliament, 2023). Recently, the EU also reached a provisional political agreement on a carbon removal certification agreement with corresponding units, encompassing permanent carbon removal, temporary carbon storage in long-lasting products, carbon farming, and soil emission reduction (Council of the European Union, 2024). The growing interest in forest-based products is particularly of prime importance for forest-rich countries like Finland, where forests cover more than 75 % of the land area, over 20 million hectares, and playing a

Abbreviations: LULUC, Land Use and Land Use Change; LULUCF, Land Use, Land Use Change, and Forestry; GWP, Global Warming Potential; GHG, Greenhouse gases; GWP_{LULUC}, Global Warming Potential from Land Use and Land Use Change; GWP_{biogenic}, Global Warming Potential from biogenic carbon flows; GWP_{fossil}, Global Warming Potential from fossil carbon emissions; LU, Land Use; LUC, Land Use Change; LCA, Life Cycle Assessment; ΔC, Change in forest carbon stock; SOC, Soil Organic Carbon; DOM, Dead Organic Matter; BAU, Business-As-Usual; PCT, Pre-Commercial Thinning; NOPCT, No Pre-Commercial Thinning; RTHIN, Reduced/Delayed Thinning with longer rotation cycle; ENW, Enhanced Energy Wood residue collection; MT, Myrtillus vegetation type; OMT, Oxalis-Myrtillus vegetation type; CT, Calluna vegetation type; VT, Vaccinium vegetation type; AWEN, Acid-hydrolysable, Water-soluble, Ethanol-soluble, Non-soluble litter fractions; C, Central Finland; C1, Äänekoski; C2, Suonenjoki; N, Northern Finland; N1, Kajaani; N2, Paltamo; S, Southern Finland; S1, Heinola; S2, Tammela.

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crucial role in the national economy (D'Amato et al., 2020).

In the carbon cycle of terrestrial ecosystems, plants take up CO₂ from the atmosphere through photosynthesis and release CO₂ into the environment through plant respiration, use of harvested biomass, and the decomposition of the biomass (Äijälä et al., 2019; Feitosa et al., 2023; Hansen et al., 2024). Biogenic emissions and removals on managed lands, i.e. changes in carbon stocks in living biomass, dead organic matter (DOM), and soil organic carbon (SOC), as well as CH₄ emissions from organic soils, represent GWP_{LULUC} emissions and removals (Eggleston, 2006). The organic soils also lead to N₂O emissions, which are included in GWP_{fossil} in accordance with the IPCC approach (IPCC, 2014). Hence, changes in carbon stock on mineral soil, for instance due to changes in land management, will only affect the GWP_{LULUC}. In the European Commission's (2021) Product Environmental Footprint guidance, the temporary carbon stored in forest products is not considered within GWP_{LULUC} but it is included under category GWP_{biogenic}. The term land use (LU) refers to the management of land, such as forest silviculture operations, while land use change (LUC) refers to human-driven changes in land use categories (ISO, 2018). The GWP_{LU} has been extensively accounted for, for instance, as part of the National GHG inventory submissions (UNFCCC, 2023). However, the understanding of the effect of forest silvicultural management practices on contributions to climate change mitigation is limited (Ameray et al., 2021). Hence, their resulting GWP_{LULUC} have also not usually been accounted for in the Life Cycle Assessment (LCA) of biobased products. This omission in LCA can be attributed to the complexities and dynamic nature of these emissions, as well as the lack of a standardized methodology of accounting for them (Järviö et al., 2018; Leinonen, 2022). Several studies have evaluated the influence the forest management practices on carbon dynamics of Finnish forests (Mäkelä et al., 2023; Mäkipää et al., 2023). For instance, Blattert et al. (2022) examined the effect of management practices based on various policies on forest ecosystem services. Akujärvi et al. (2021) studied the effect of energy wood collection on carbon dynamics at a landscape-level by combining the stand-level simulation with southern boreal landscape-level inventory data in Finland. Recently, Mäkelä et al. (2023) examined the carbon sequestration and biodiversity effects of low harvest and no harvest management practices compared to the business as usual scenario using the PREBAS simulator. While GWP_{LULUC} removals were directly affected by the harvest level, biodiversity was influenced by other management practices and relatively unaffected by changes in carbon stock. Mäkipää et al. (2015) simulated conventional stem-only harvesting, whole-tree harvesting, and whole-tree harvesting excluding needles.

The product level GWP_{LULUC} can be evaluated using either a top-down or a bottom-up approach (Lehtilä et al., 2025a). The choice of either top-down or bottom-up approach is dependent on the goal and scope of the assessment. When assessing the average national or regional GWP_{LULUC} emissions or removals, the top-down approach is the only option. The national or regional emissions or removals are a combined result of changes of the land use and management practices in all individual forest stands within that area, but it is not possible to quantify all these changes separately. Therefore, in such cases, the required GWP_{LULUC} data must be obtained from national or regional inventories.

In contrast, when the effects of specific changes in the land use or management practices on specific forest sites are considered, the bottom-up approach must be used. The reason for this is that although the top-down approach can allocate the GWP_{LULUC} emissions or removals to land-based products originating from the area of the assessment, that approach cannot identify separate management practices, as mentioned above. Therefore, such assessments need to be carried out using process-based analyses at a stand level. Further, since long-term stand-level inventory data are rarely available, modelling approaches are usually necessarily used to quantify the effects of each change in management practices. Lehtilä et al. (2025a) used a top-down approach (also known as “statistical LUC” in some carbon footprinting guidelines)

allocating the total annual GWP_{LULUC} emissions from Finnish forests to the total harvested biomass to estimate the GWP_{LULUC} of harvested biomass in terms of kg CO₂ eq/m³ at the national level in Finland. A similar approach was employed by Lehtilä et al. (2025b) to assess GWP_{LULUC} at the provincial level, and by Ghani et al. (2025) to evaluate the GWP_{LULUC} of sawdust-based bioethanol at the national level in selected European countries. In contrast, the current study demonstrates, for the first time, the application of the GWP_{LULUC} framework by Lehtilä et al. (2025a) using a process-based bottom-up approach to evaluate the effects of changes in forest management practices.

The objective of this study was to examine GWP_{LULUC} including both LULUC related emissions and removals of forest-based products (i.e., harvested wood raw material) from mineral soils considering the effect of various forest management scenarios in comparison to a standard practice “business-as-usual” (BAU) scenario in Finland. The results of land occupation are also presented, considering their relevance to biodiversity. The effect of forest management practices considered a comprehensive range of silvicultural practices, including factors such as collecting harvesting residues during thinning, and ensuring that the proportion of collected harvesting residues (treetops and branches) is included in the assessment. The management practices were defined in collaboration with industry partners to better reflect what is technically feasible during clear-cutting and to ensure compatibility with the general forest management recommendations in Finland (known as Tapio's recommendations), thereby enhancing their practical applicability. We focused on birch, pine, and spruce due to their prominence in Finnish ecosystems and their significance in timber production. Additionally, in one scenario, the study considered the collection of smaller-diameter tree parts, to be used as a raw material of renewable fuels, and therefore included them in the total harvested wood, underscoring their economic and environmental importance. To our knowledge, this was the first time in Finland that such a comprehensive, management-specific assessment on the product-level GWP_{LULUC} has been conducted.

2. Methodology

In this study, we apply the “bottom-up” approach to quantify the product level GWP_{LULUC} emissions and removals. This approach is process-based, and it identifies the changes in land use or land management that are specifically related to production of a certain product. The GWP_{LULUC} emissions are accounted for only in cases where they are a result of changes in land use or land management, and allocated to products within an amortization period. In the case of forestry production, the amortization period is the whole rotation cycle, as specified by the PAS 2050: 2011 carbon footprinting guidelines (BSI, 2011). If there are no changes in land use or management, the products have zero GWP_{LULUC} emissions.

This study focused on the effects of management practices considering forest grown on mineral soils, and to assess the effects of such practices, stand-level modelling analyses were carried out. Following the bottom-up approach, the changes of the forest carbon stock were quantified when the management was changed from BAU to an alternative management practice.

The effect of management practices on the GWP_{LULUC} emissions and removals of forest products was evaluated with stand-level simulation of scenarios with change in forest management practices by following an integrated approach, as shown in the Fig. 1. Firstly, a comprehensive description of scenarios was created to cover the relevant practices in Finnish forestry. This was followed by running these scenarios with the MOTTI stand simulator. The collection of logging residues will also affect SOC stock changes; therefore, in such scenarios, the soil carbon model Yasso was used to evaluate the changes in the soil carbon stock. The GWP_{LULUC} related to changes in forest management were quantified by comparing the forest carbon stock achieved with the alternative management practice to the carbon stock in the BAU management practice, and finally allocating the change in the carbon stock to the

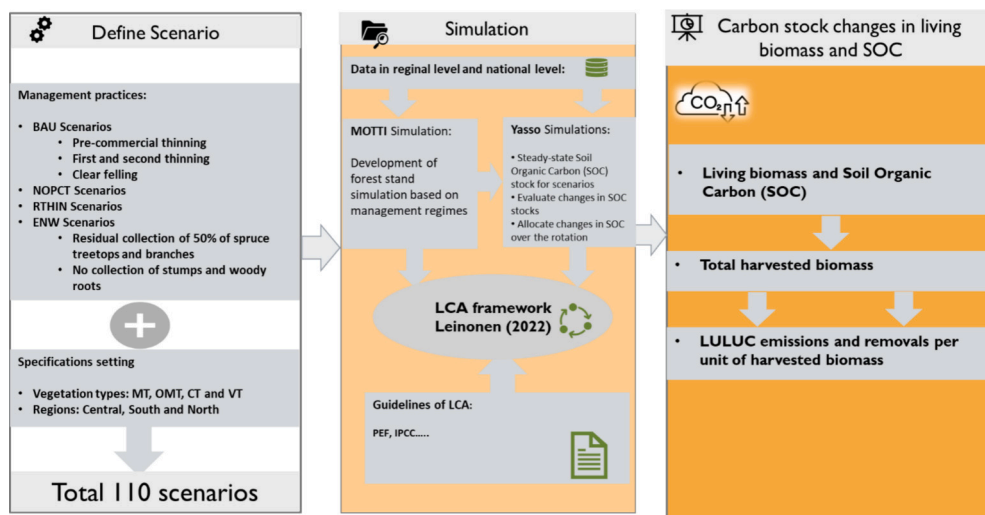


Fig. 1. The procedure to estimate the GWP_{LULUC} of forest products with changes in management. BAU: business-as-usual; NOPCT: No pre-commercial thinning; RTHIN: No pre-commercial thinning followed by delayed and heavier thinnings; ENW: Collection of 50 % of spruce treetops and branches; MT: *Myrtillus* vegetation; OMT: *Oxalis-Myrtillus* vegetation; CT: *Calluna* vegetation; VT: *Vaccinium* vegetation; SOC: soil organic carbon.

harvested biomass. The details of each step are provided in Fig. 1.

2.1. Description of scenarios

A comprehensive list of scenarios was considered based on management practices, tree species, and vegetation types across different regions of Finland to comprehensively evaluate the GWP_{LULUC} effects of changes in forest management practices, as described below.

2.1.1. Management practices

Firstly, the BAU forest management scenario was considered, guided by Tapio's Good Forest Management Practices (Tapio, 2023), Kemera regulation which enables private forest owners to receive support for sustainable forestry practices (Metsäkeskus, 2023), and industry standards. The BAU scenario includes pre-commercial thinning, followed by two thinnings and then final felling.

During pre-commercial thinning (PCT), the trees to be removed are selected according to the following criteria. The timing, based on the size reached by the trees, depends on the site and species considered (usually the thinning is carried out when the trees have reached about 3–6 m dominant height). After PCT, a maximum of 3000 trees per hectare is allowed to remain. In spruce stands only, the stems of the trees harvested were collected to be used as energy source, following Tapio's forest management practices (Tapio, 2023). Commercial thinnings, or simply thinnings, are then usually carried out for various reasons, such as removing damaged trees, providing more space to remaining trees, and obtaining an early income. In our scenarios, the timing of the thinnings and the stand density targets are outlined for different tree species and sites, again based on the size reached by the trees. For spruce and pine-dominated stands, the aim is to leave between 1200 and 900 trees per hectare; while for birch-dominated stands, the target stand density is set at 800–700 trees per hectare. In our scenarios, the initiation of the first commercial thinning occurred at the age of around 30–40 years, and a second thinning was also required in all stands. Thinnings were carried out prioritizing the removal of smaller and suppressed trees, and resulted in removing around 30 % of the growing stock. Then, the final felling is implemented when either a certain mean diameter size or age threshold is reached, whichever first occurs, again depending on site and species. In our simulations, the size threshold was always reached first, and final felling happened consequently around at the age of 60–80 years. No residues were collected during the final felling under BAU.

Then, additional forest management scenarios were considered with various practices different from BAU for harvesting residue collection, pre-commercial thinning, and first thinning. The representative scenarios were selected to explore options to increase the forest carbon stock (Luke, 2024) and to demonstrate the effect of the demand for additional residues to produce renewable fuels on the forest carbon stock (Ghani et al., 2025), as well as to demonstrate the implementation of the GWP_{LULUC} framework in evaluating the effect of management practices at the product level. Specifically, the alternative scenarios are described below.

NOPCT scenario considered no pre-commercial thinning, and then otherwise the management practices following the same guidelines as BAU. RTHIN scenario considered no pre-commercial thinning followed by only one (spruce) or two (pine and birch) delayed and heavier thinning(s). On average, we considered a 10 years delay in thinning and 40 % removals of the growing stock. In RTHIN, the final felling also was delayed compared to BAU in order to meet the criteria for average stand-size at final felling. Finally, ENW scenario is considered for spruce by otherwise managing the stands according to BAU but collecting 50 % of the logging residue treetops and branches) from the final felling. The 50 % collection rate of the residues was selected arbitrarily for demonstration purposes, as 100 % collection is not technically possible, and very low collection rates are not commercially feasible.

2.1.2. List of scenarios

For each main tree species of Finland (Puuinfo, n.d), namely Silver Birch (*Betula pendula* Roth), Norway Spruce (*Picea abies* Karst), and Scots Pine (*Pinus sylvestris* L.), stands were generated in two municipalities located in three regions: South, Central, and Northern Finland (see Table 1). In each municipality, two stands with different vegetation types were created: Myrtillus type (MT) and Oxalis-Myrtillus type (OMT) for spruce and birch, and Vaccinium type (VT) and Calluna type (CT) for pine. The list of scenarios is available in Table 1.

2.2. Forest stand and soil carbon simulations

2.2.1. MOTTI forest simulation

MOTTI is a decision-support tool that assesses the impact of forest management strategies on stand dynamics and financial viability of forestry (Hynynen et al., 2014). This tool has been employed in various scenario analyses to investigate the enduring effects of forest management on biomass supply and the development of forest resources in

Table 1
Description of scenarios of simulated stands on different locations.

Location	Municipality	Species	Vegetation/ management	Abbreviation		
Central	Äänekoski (C1)	Spruce	MT/BAU	C1-MT_BAU		
			MT/NOPCT	C1-MT_NOPCT		
			MT/RTHIN	C1_MT_RTHIN		
			OMT/BAU	C1-OMT_BAU		
			OMT/NOPCT	C1-OMT_NOPCT		
			OMT/RTHIN	C1_OMT_RTHIN		
			MT/BAU/ENW	C1-MT-BAU-ENW		
			Birch	OMT/BAU/ENW	C1-OMT-BAU-ENW	
				CT/BAU	C1-CT_BAU	
				CT/NOPCT	C1-CT_NOPCT	
		CT/RTHIN		C1_CT_RTHIN		
		VT/BAU		C1-VT_BAU		
		VT/NOPCT		C1-VT_NOPCT		
		Suonenjoki (C2)	Pine	VT/RTHIN	C1_VT_RTHIN	
				MT/BAU	C2-MT_BAU	
				MT/NOPCT	C2-MT_NOPCT	
				MT/RTHIN	C2_MT_RTHIN	
				OMT/BAU	C2-OMT_BAU	
				OMT/NOPCT	C2-OMT_NOPCT	
				OMT/RTHIN	C2_OMT_RTHIN	
	CT/BAU			C2-CT_BAU		
	CT/NOPCT			C2-CT_NOPCT		
	CT/RTHIN			C2_CT_RTHIN		
	Spruce		VT/BAU	C2-VT_BAU		
			VT/NOPCT	C2-VT_NOPCT		
			VT/RTHIN	C2_VT_RTHIN		
			MT/BAU	N1-MT_BAU		
			MT/NOPCT	N1-MT_NOPCT		
			MT/RTHIN	N1_MT_RTHIN		
			OMT/BAU	N1-OMT_BAU		
			OMT/NOPCT	N1-OMT_NOPCT		
			OMT/RTHIN	N1_OMT_RTHIN		
			MT/BAU/ENW	N1-MT-BAU-ENW		
	Kajaani (N1)	Spruce	OMT/BAU/ENW	N1-OMT-BAU-ENW		
			CT/BAU	N1-CT_BAU		
			CT/NOPCT	N1-CT_NOPCT		
			CT/RTHIN	N1_CT_RTHIN		
			VT/BAU	N1-VT_BAU		
			VT/NOPCT	N1-VT_NOPCT		
			VT/RTHIN	N1_VT_RTHIN		
			MT/BAU	N2-MT_BAU		
			MT/NOPCT	N2-MT_NOPCT		
			MT/RTHIN	N2_MT_RTHIN		
		Birch	OMT/BAU	N2-OMT_BAU		
			OMT/NOPCT	N2-OMT_NOPCT		
			OMT/RTHIN	N2_OMT_RTHIN		
			CT/BAU	N2-CT_BAU		
			CT/NOPCT	N2-CT_NOPCT		
			CT/RTHIN	N2_CT_RTHIN		
			VT/BAU	N2-VT_BAU		
			VT/NOPCT	N2-VT_NOPCT		
			VT/RTHIN	N2_VT_RTHIN		
			MT/BAU	S1-MT_BAU		
	Paltamo (N2)	Pine	MT/NOPCT	S1-MT_NOPCT		
			MT/RTHIN	S1_MT_RTHIN		
			OMT/BAU	S1-OMT_BAU		
			OMT/NOPCT	S1-OMT_NOPCT		
			OMT/RTHIN	S1_OMT_RTHIN		
			MT/BAU/ENW	S1-MT-BAU-ENW		
			Spruce	OMT/BAU/ENW	S1-OMT-BAU-ENW	
				CT/BAU	S1-CT_BAU	
				CT/NOPCT	S1-CT_NOPCT	
				CT/RTHIN	S1_CT_RTHIN	
		VT/BAU		S1-VT_BAU		
		VT/NOPCT		S1-VT_NOPCT		
		VT/RTHIN		S1_VT_RTHIN		
		MT/BAU		S2-MT_BAU		
		MT/NOPCT		S2-MT_NOPCT		
		MT/RTHIN		S2_MT_RTHIN		
		Heinola (S1)	Pine	OMT/BAU	S2-OMT_BAU	
				OMT/NOPCT	S2-OMT_NOPCT	
				OMT/RTHIN	S2_OMT_RTHIN	
				MT/BAU	S2-MT_BAU	
	MT/NOPCT			S2-MT_NOPCT		
	MT/RTHIN			S2_MT_RTHIN		
	Tammela (S2)			Spruce	OMT/BAU	S2-OMT_BAU
					OMT/NOPCT	S2-OMT_NOPCT
					OMT/RTHIN	S2_OMT_RTHIN
					MT/BAU	S2-MT_BAU
		MT/NOPCT	S2-MT_NOPCT			
		Birch	MT/RTHIN	S2_MT_RTHIN		
			OMT/BAU	S2-OMT_BAU		
			OMT/NOPCT	S2-OMT_NOPCT		
			OMT/RTHIN	S2_OMT_RTHIN		
			MT/BAU	S2-MT_BAU		

Table 1 (continued)

Location	Municipality	Species	Vegetation/ management	Abbreviation	
			OMT/NOPCT	S2-OMT_NOPCT	
			OMT/RTHIN	S2_OMT_RTHIN	
			CT/BAU	S2-CT_BAU	
			CT/NOPCT	S2-CT_NOPCT	
			CT/RTHIN	S2_CT_RTHIN	
			VT/BAU	S2-VT_BAU	
			VT/NOPCT	S2-VT_NOPCT	
			Pine	VT/RTHIN	S2_VT_RTHIN

Note: BAU: business-as-usual; NOPCT: No pre-commercial thinning; RTHIN: No pre-commercial thinning with delayed and heavier thinnings; ENW: Collection of 50 % of spruce treetops and branches; MT: *Myrtillus* vegetation; OMT: *Oxalys-Myrtillus* vegetation; CT: *Calluna* vegetation; VT: *Vaccinium* vegetation. Central Finland: C1: Äänekoski; C2: Suonenjoki; Northern Finland: N1: Kajaani; N2: Paltamo; South: S1: Heinola; S2: Tammela.

Finland (e.g., Haikarainen et al., 2021). MOTTI has been originally calibrated using a wide dataset of commercial stands all across Finland, a subset of the National Forest Inventory (NFI) from the 1970s–1990s covering all the combinations of site and species, and it is constantly recalibrated with new NFI data from the whole country (Hynynen et al., 2014, 2015).

In the MOTTI stand simulator, various management regimes, including cuttings, silvicultural treatments, and no-treatments, can be generated, and simulated to assess stand dynamics under different scenarios, either according to silvicultural prescriptions or manual input (Hynynen et al., 2014, 2015). This approach facilitates the extraction of data on carbon stock increase and decrease in Finnish forests over five-year intervals, considering various scenarios and regions (Luke, n.d.).

Virtual forest stands were created with the MOTTI stand simulator over their rotation cycle, considering the scenarios mentioned in Table 1 (Hynynen et al., 2014). The software generates forest regeneration, with soil preparation methods and type of regeneration specific for each geographical location (i.e., municipality) and site characteristics (i.e., vegetation type specified by Cajander (1949). Further management activities were implemented as described earlier.

2.2.2. Yasso soil carbon modelling for residue collection

Yasso07 is a dynamic model that simulates SOC cycling in mineral soils (Tuomi et al., 2009). The input data needed for Yasso07 modelling includes air temperature, precipitation, and litter input from plant above-ground and below-ground residues – including foliage, fine roots, branches, coarse roots, stems, stumps, and ground vegetation. As an output, Yasso07 provides the annual changes in soil carbon stock in a soil layer of 1 m, considering weather impact and the different decomposition rates of litter and humus SOC fractions (Tuomi et al., 2009). Yasso07 has been used widely in research and also in the National Greenhouse Gas Inventory of Finland (Statistics Finland, 2023).

In this study, Yasso07 was applied to estimate the effect of management changes in the SOC of forest land. The modelling was conducted only for a representative set of spruce, grown in Municipality 1: Äänekoski (Central Finland, C1), (Supplementary information SI 1; Table 1). Both vegetation types (OMT and MT) were included in Yasso07 modelling. The scenarios BAU and ENW were compared with Yasso07 modelling.

The Yasso07 model was run by specifying constant input variables; that is, only the litter input from final felling was changed, while other inputs, such as litter from the upper 1 m of soil, existing soil carbon, and litter input during the rotation cycle, were assumed to remain constant. The model simulations were then repeated for multiple years using these variables. The weather data used was the average annual temperature (2.9 °C) and annual precipitation sum (609 mm) in Finland in 1990–2010 (FMI, 2024). The objective of the study was to evaluate only the effect of management change, i.e., the impact of residue collection,

not the effect of different climate conditions; therefore, average Finnish meteorological data were used. The litter inputs from branches and stems (as kg/ha/yr) were calculated based on MOTTI data. The amount of dry matter (m^3/ha) of the branches and stems of MOTTI clear felling data was first divided by the number of years of the rotation period to get the average annual litter input as per the Yasso's requirement. Then, the volume was converted to mass by multiplying it with the average density of coniferous sawlogs and pulplogs (405 kg/m^3) (UNECE, 2010). Litter input was considered only from branches and stems, while other sources of litter input were excluded, as the effect of management change in branch and living stem carbon inputs was estimated. The carbon content of 0.50 was assumed for all litter inputs (IPCC, 2006). The chemical quality of litter input (AWEN fractions) was based on Akujärvi et al. (2014). The assumed average diameter of the logging residues was considered as 3 cm based on discussion with industry experts.

The Yasso07 simulations based on the described constant annual input data were run for each scenario listed in Supplementary information (please refer to SI 1: Table 1 and 2) until a steady-state carbon stock (kg C/ha) was reached (i.e., equilibrium, no more changes in SOC between the years). The steady-state SOC stocks between the scenarios were compared, and the predicted increase or decrease in SOC ($\Delta C_{\text{SOC, mineral}}$) was allocated to total harvested biomass (HB) within a single harvest rotation following PAS2050:2011 (BSI, 2011), as follows:

$$\Delta C_{\text{SOC, mineral}} = \frac{(SOC_{\text{BAU}} - SOC_{\text{BAU-ENW}})}{HB} \text{ (kg C/m}^3\text{)} \quad (1)$$

2.3. Calculation of GWP_{LULUC} emissions and removals

In this study, GWP_{LULUC} emissions and removals were evaluated using a mass balance-based approach, where changes in steady-state carbon (C) stock are allocated to harvested products, aligning with established guidelines such as ISO14067:2018 (ISO, 2018). We have considered forest stands on mineral soils; therefore, GWP_{LULUC} results solely from carbon stock changes, with no CH_4 emissions. The functional unit is defined as the production of 1 m^3 of harvested wood in Finland. This harvested wood serves as the raw material for subsequent products and facilitates comparison and interpretation of the results by relevant

stakeholders.

The modelling principle is demonstrated in Fig. 2. The temporary fluctuation of carbon stock is indicated by the solid blue line and the average carbon stock over the rotation cycle is shown by the broken red line. In this example, the carbon stock changes are allocated to all the products which are obtained within the period from T1 to T3. For instance, the initial carbon stock (e.g., natural vegetation) of a forest stand is C_0 and the average carbon stock after a land use change activity is denoted as C_1 and the emissions related to this change of the carbon stock are allocated to products harvested at the point T1. Assuming that there are no further changes in the management practices (e.g. between time points T1 and T2), there will be no management-related changes in the carbon stock either, so the GWP_{LULUC} for this period would be zero. In contrast, if there are subsequent changes in the management practices that would further change the carbon stock (e.g. from C_1 to C_2), these changes would need to be taken into account and the related emissions or removals should be allocated to products obtained at the harvest at point T3.

GWP_{LULUC} emissions and removals of products are evaluated by equally allocating the carbon stock changes to the products obtained within a fixed-term amortization period, the length of which is a single harvest rotation (more details on fixed-term amortization period available in Lehtilä et al. (2025a)). The base case time period was defined as the average carbon stock under the BAU scenario. GWP_{LULUC} was calculated using the Eq. (2) given below.

$$GWP_{\text{LULUC}} = rc \times \frac{44}{12} \text{ (kg CO}_2\text{ eq./m}^3\text{)} \quad (2)$$

where GWP_{LULUC} is the GWP associated with LULUC and rc is the ratio between change of forest carbon stocks and harvested biomass which is used to determine the change in forest carbon stocks per unit volume of harvested biomass. Eq. (3) below is used to calculate the rc .

$$rc = \frac{\Delta C}{HB} \text{ (kg C/m}^3\text{)} \quad (3)$$

Here, ΔC (units: kg C/ha/rotation) represents the change in forest C within a harvest rotation, and is the difference between the C stocks at the beginning of the harvest rotation (C_1) and at the end of the harvest

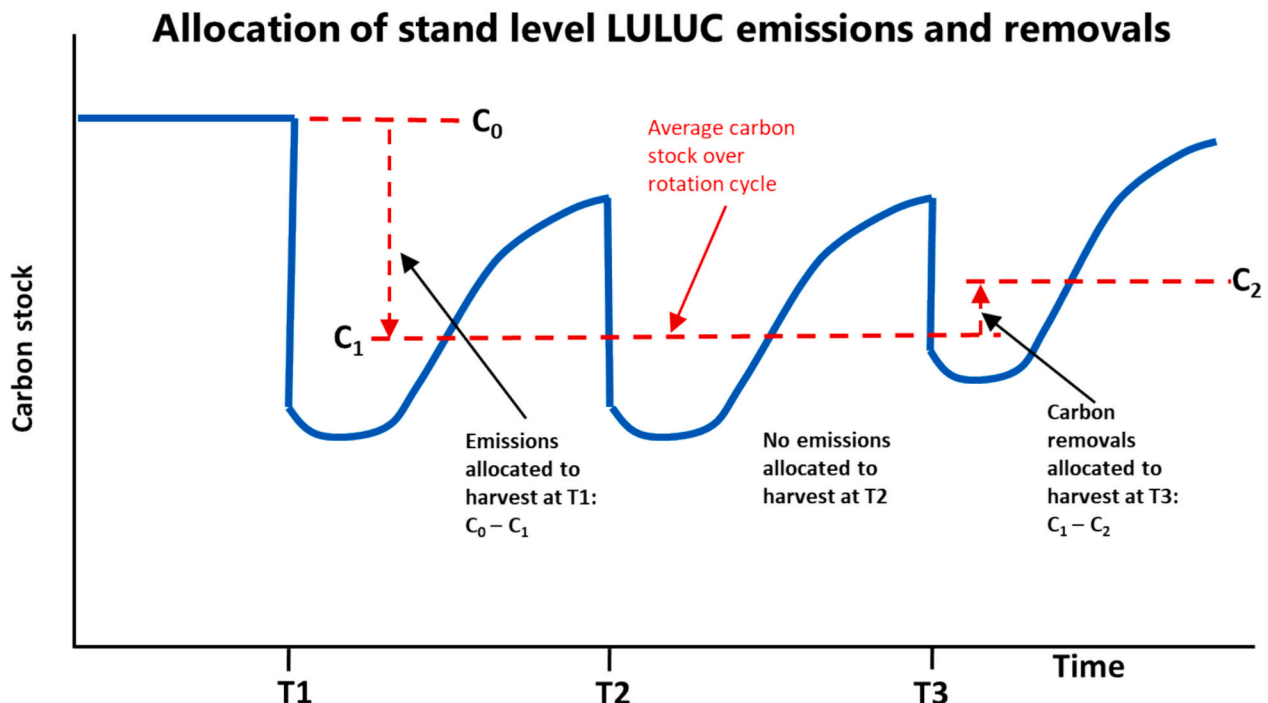


Fig. 2. Management induced changes in carbon stock of a forest stand (based on Leinonen, 2022). T: Time period; C: Carbon stock.

rotation (C_2). HB (units: $m^3/ha/rotation$) represents the total harvested biomass within one harvest rotation. ΔC encompasses changes in carbon stocks in living biomass, DOM, and SOC stocks, calculated using Eq. (4).

$$\Delta C = \Delta C_{LB} + \Delta C_{DOM} + \Delta C_{SOC} \text{ (kg C/ha/rotation cycle)} \quad (4)$$

where ΔC_{LB} is the carbon stock change in living biomass, ΔC_{DOM} is the net carbon stock change in DOM, and ΔC_{SOC} is the net SOC stock change in mineral and organic soils within a harvest rotation. More detailed formulas for the compounds of ΔC are presented in Lehtilä et al. (2025a).

Overall, the changes in management practices from BAU to NOPCT or RTHIN, considering different regions, species and vegetation as described in the scenarios would affect the ΔC_{LB} while ENW scenarios would impact the ΔC_{SOC} . Other parameters would remain the same. We have presented the results of carbon stock changes with changes in management practices in terms of GWP_{LULUC} to make it easier for readers and LCA practitioners to apply the same method with different practices regardless of changes in any carbon pool. Furthermore, this approach enhances compatibility for presenting GWP_{LULUC} results from changes in management practices in combination with GWP_{LULUC} results at regional or landscape levels.

3. Results

3.1. GWP_{LULUC} results with change in management practices

The GWP_{LULUC} of $1 m^3$ of harvested spruce wood for different scenarios with change in forest management practices is illustrated in Fig. 3. In comparison to the BAU scenario, spruce wood harvested with NOPCT exhibits mainly a minimal effect only with no apparent trend, while scenarios involving RTHIN result in significant GWP_{LULUC} removals across all scenarios in both municipalities. Specifically, NOPCT leads to emissions of approximately $50 \text{ kg CO}_2 \text{ eq/m}^3$ in only one scenario (N1-MT), while in other cases (C1-OMT, N1-OMT, and S1-MT, C2-OMT, and N2-OMT), it results in smaller emissions ranging from approximately 3 to $10 \text{ kg CO}_2 \text{ eq/m}^3$. Conversely, in the other spruce scenarios NOPCT results in GWP_{LULUC} removals ranging from around $-10 \text{ kg CO}_2 \text{ eq/m}^3$ (i.e., in C1-MT scenario) to around $-51 \text{ kg CO}_2 \text{ eq/}$

m^3 (i.e., in S1-OMT scenario). Spruce RTHIN consistently results in GWP_{LULUC} removals across all scenarios, ranging from approximately $-26 \text{ kg CO}_2 \text{ eq/m}^3$ to $-206 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood.

In the case of birch (please refer to Fig. 4), NOPCT scenarios generally lead to GWP_{LULUC} removals, except for the N1-MT and S2-OMT scenario where it resulted in emissions for approximately $14 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood and $56 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood, respectively. The GWP_{LULUC} removals for other NOPCT scenarios ranges from -19 to $-73 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood. Conversely, RTHIN results in substantial GWP_{LULUC} removals, for both municipalities ranging from approximately -26 to $-103 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood.

For the NOPCT scenarios, harvesting pine wood generally results in removals or small emissions, except for S2-CT and S2-VT where it resulted emissions of around $22 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood (Fig. 5). However, the removals for NOPCT are relatively modest, ranging from -5 to $-33 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood, compared to the more substantial removals observed in RTHIN scenarios, which vary from -24 to $-193 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood.

3.2. Effect of residue collection on GWP_{LULUC} results

Considering GWP_{LULUC} , the collection of residues, as exemplified in the ENW collection for spruce, results in losses of SOC resulting in GWP_{LULUC} emissions ranging from 29 to $30 \text{ kg CO}_2 \text{ eq/m}^3$ of harvested wood (please refer to Fig. 6). However, the removal of logging residuals results in only a nominal reduction of the forest’s carbon stock. This GWP_{LULUC} emission is also negligible at the product level, especially when comparing biobased and fossil products, such as fuels. In such cases, the emissions from carbon stock change are small compared to the climate benefits that can be obtained when replacing fossil materials with biobased ones. For example, the GWP_{LULUC} emissions due to the losses of SOC, as mentioned above, will result in only around 0.05 to $0.06 \text{ kg CO}_2 \text{ eq./l}$ of E20 (i.e., 20 % blend of bioethanol with gasoline) fuel use. The use of E20 would therefore still result in around 14 % lower fossil GHG emissions and 13 % lower overall GHG emissions (Ghani et al., 2025; Lehtilä et al., 2025b).

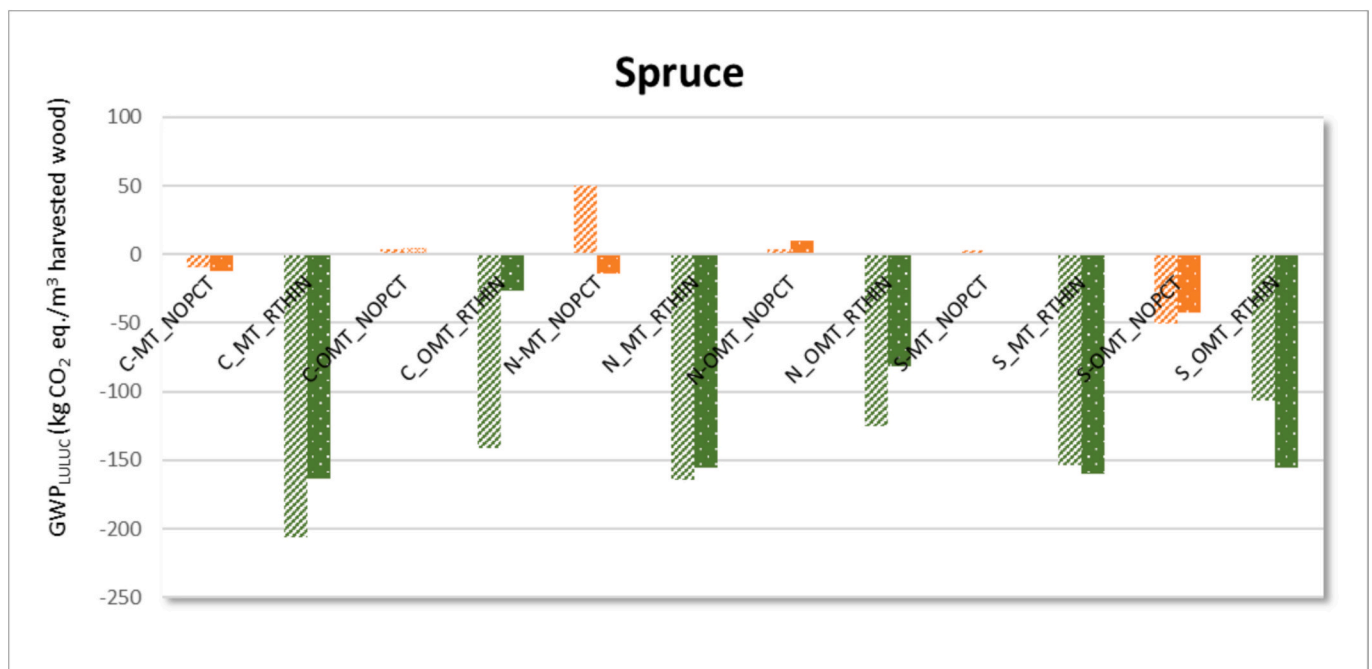


Fig. 3. GWP_{LULUC} of $1 m^3$ of harvested wood due to ΔC_{LB} when changing the management practices from BAU to alternative scenarios.

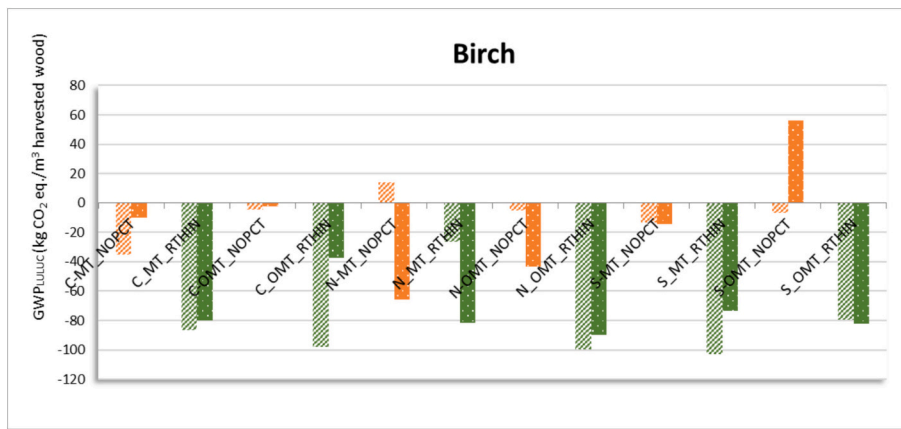


Fig. 4. GWP_{LULUC} of 1 m³ of harvested wood for different scenarios due to ΔC_{LB} when changing the management practices from BAU to alternative scenarios.

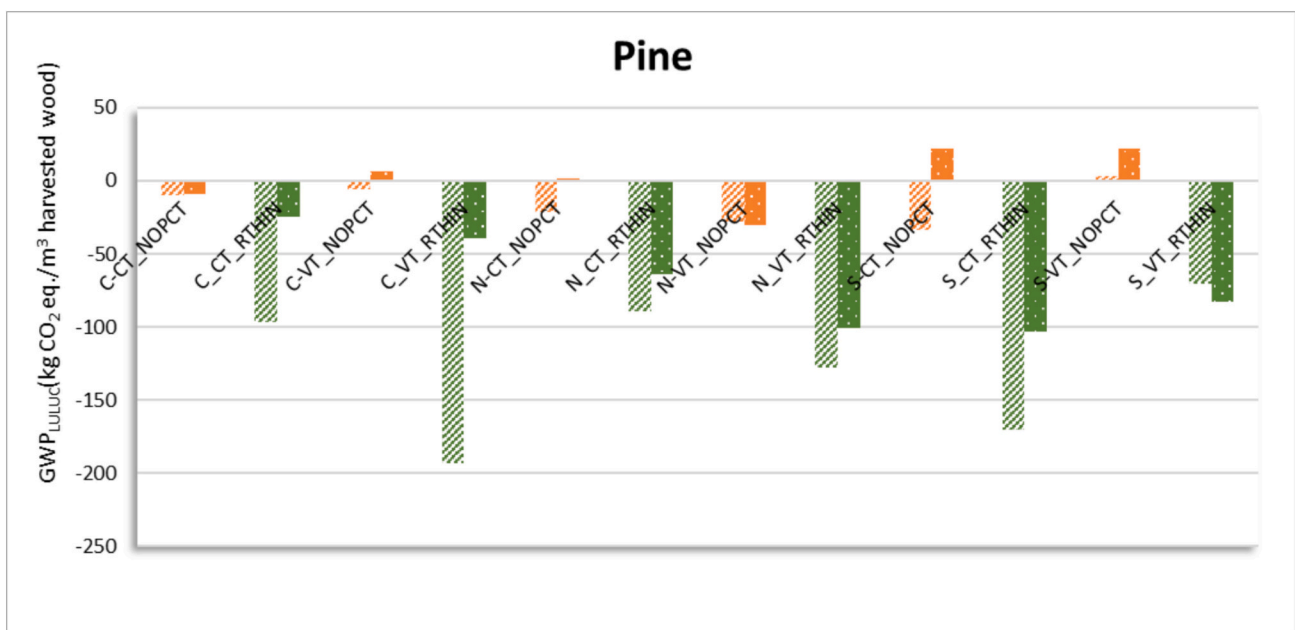


Fig. 5. GWP_{LULUC} of 1 m³ of harvested wood for different scenarios due to ΔC_{LB} when changing the management practices from BAU to alternative scenarios.

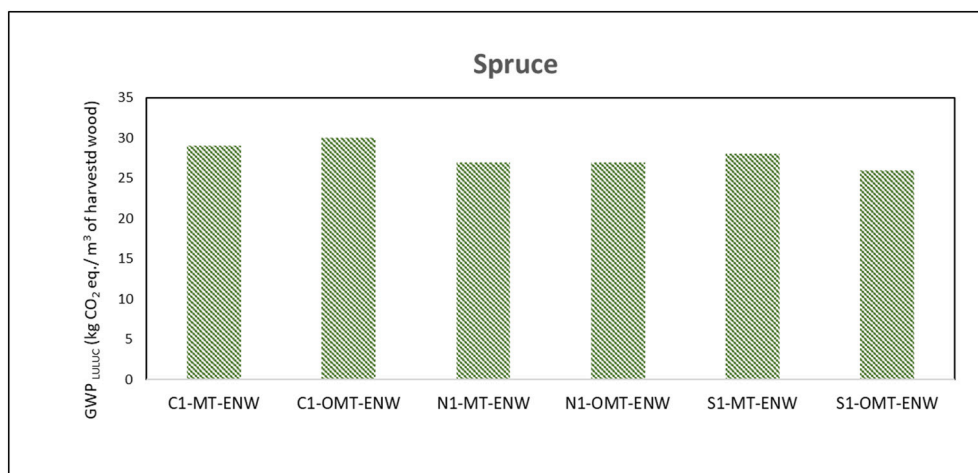


Fig. 6. GWP_{LULUC} of 1 m³ of harvested wood for different scenarios due to ΔC_{SOC} when changing the management practices from BAU to ENW.

3.3. Land occupation

The study investigated the land required to produce 1 m³ of wood annually, highlighting its inverse relationship with the average annual harvest rate per hectare. This land occupation metric is vital for assessing biodiversity impact, a key indicator of sustainability (Semenchuk et al., 2022). Fig. 7 shows that when involving the same regional factors, vegetation types, and management practices, pine required the most land, while spruce required the least across all scenarios. The BAU scenarios typically showed the smallest harvested volumes and, consequently, the highest land occupation, whereas the RTHIN scenarios often resulted in the lowest land occupation.

4. Discussion

The NOPCT, RTHIN, and ENW practices for different species and regions in Finland were selected to assess the effects of increased biomass harvesting in light of declining carbon sinks in Finland (Luke, 2024) and rising raw material demand (Luke, 2023). Overall, our findings show that the effect of the management practices considered in this study on GWP_{LULUC} is quite consistent, although there is some variation depending on different regions and forest site types, even within the same species. On average, changes in management practices from BAU to NOPCT and RTHIN improve the carbon sequestration potential and land-use efficiency of forest-based products.

Implementing RTHIN scenarios proved to result in consistent and significant GWP_{LULUC} removals (−24 to −206 kg CO₂ eq/m³ of harvested wood), making it an effective method for increasing carbon removals from the atmosphere. This is primarily due to differences in biomass growth patterns and silvicultural activities over the forest rotation cycle. An increased carbon sink is expected with delayed thinning, particularly due to the resulting delayed final felling. The latter was not an explicitly requested feature of the scenario but rather a natural consequence of the delayed thinning. For example, in MT spruce forests in Municipality 1 of the Central Region, biomass accumulation is nearly identical up to year 30. However, by age 49, the RTHIN scenario results in 74 % more biomass than BAU. By the end of the rotation cycle (62 years for BAU and 80 years for RTHIN), RTHIN yields approximately 61 % more biomass overall. A similar pattern was observed for both Birch and Spruce as well, for example when comparing MT and CT vegetation types in Municipality 1 of the central region (please refer to Supplementary information SI 1: Table 4).

However, the other less intensive management NOPCT scenarios results in relatively small and inconsistent sequestration. For example, in most cases, it resulted in GWP_{LULUC} removals (−5 to −73 kg CO₂ eq/

m³ of harvested wood), while in other cases, there were small GWP_{LULUC} emissions (3 to 56 kg CO₂ eq/m³ of harvested wood). This trend can also be illustrated using the example of spruce forests in a municipality 1 of the Central Region. In this case, growth remains nearly the same for the first 40 years. However, by age 52, the NOPCT scenario shows 7 % more growth than BAU. By the end of the rotation cycle (62 years for NOPCT and 65 years for BAU), growth in NOPCT decreases by around 11 %. This decline is due to an additional thinning in NOPCT at age 52, which also leads to around a 2 % increase in average biomass compared to BAU. This additional biomass explains the slight net sequestration observed in NOPCT spruce forests in Municipality 1 of the Central Region. However, this pattern does not hold for NOPCT spruce in Municipality 1 of the Northern Region, where average biomass is around 11 % lower than in the BAU scenario, leading to overall emissions instead of sequestration. Confounding effects may arise from naturally regenerated species that are not removed during the juvenile phase. These species, which vary in occurrence depending on region and site, may have different growth patterns from the main species and may be removed during later thinning. Similar to the RTHIN scenarios, Birch and Pine showed trends comparable to Spruce when considering MT and CT vegetation in the municipalities of the central region (see Supplementary information SI 1: Table 4).

These findings are important, especially in light of recent concerns about declining carbon sinks in Finland (Luke, 2024), and could support improved carbon sequestration, for example by applying RTHIN practices, particularly in regions where the GWP_{LULUC} of forest products currently results in emissions rather than sequestration (Lehtilä et al., 2025b).

The central region showed predominant sequestration, with some scenarios resulting in negligible emissions, while the southern and northern regions also showed sequestration, though some scenarios resulted in significant emissions.

Considering the species perspective, pine showed the highest land occupation. The southern region is the most efficient in terms of land occupation, while the northern region requires the most land to produce the same amount of wood.

Overall, it can be noted that the RTHIN scenarios are the most beneficial case of the both environmental indicators considered in this study, offering potential advantages in terms of both higher carbon sequestration and more efficient land use, while also resulting in the highest total wood harvest compared to the other management practices (see Supplementary information SI 1: Table 3).

The European Union has set a target of 5.5 % for biofuels from non-food and synthetic sources as part of renewable energy use in the transport sector (European Union, 2023). One option for producing

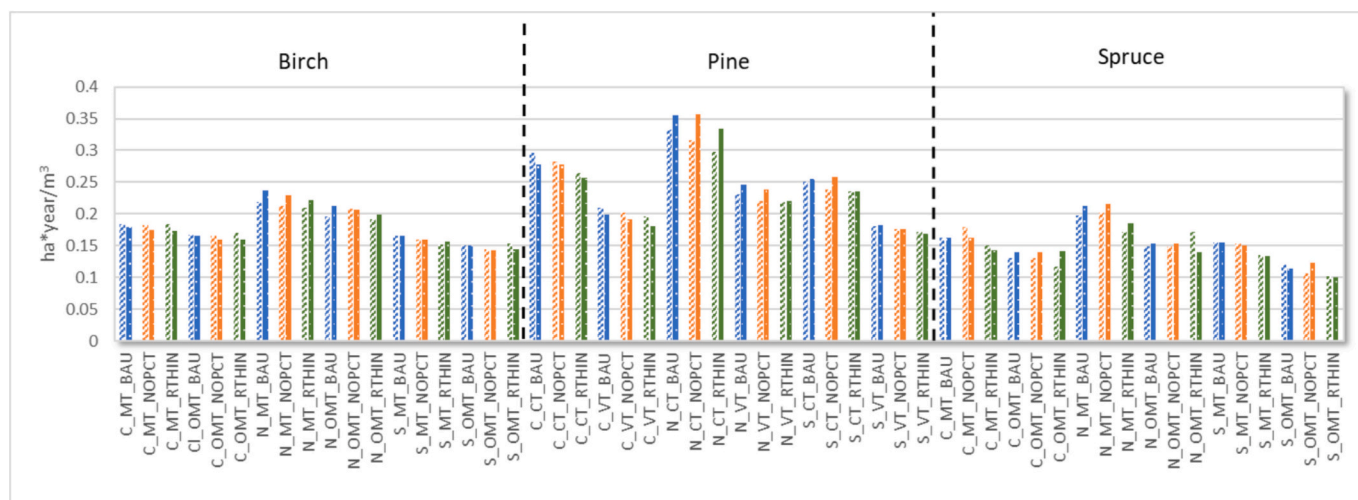


Fig. 7. Simulated land occupation of birch, pine, and spruce in different regions under selected vegetation types and management practices.

biofuels is to use the by-products of forest industry as raw materials. However, Ghani et al. (2025) have shown that bioethanol from sawdust can meet only 0.5 % of the sector's total fuel consumption in the European Union. Therefore, additional raw material is needed from other sources, including forest residues that are not currently used for commercial purposes. Both the residues from final felling and the small-diameter stems from the precommercial thinning could be considered a promising raw material option for example for bioethanol production or for sustainable aviation fuels, to help meet the renewable energy targets. Although residue collection or the precommercial thinning typically reduce forest carbon stocks, the resulting LULUC emissions per cubic meter of harvested wood are negligible compared to the climate benefits achieved by replacing fossil fuels with biofuels (Lehtilä et al., 2025b; Ghani et al., 2025).

From a species and site perspective, the GWP_{LULUC} results show some variation, suggesting the need for stand-specific evaluation at the highest level of aggregation possible. However, considering the complex nature of natural forest processes, it was not possible to pinpoint the reasons behind the variable behavior, especially for the outliers or different behavior in different municipalities of same region, and this was considered outside the scope of the study. In any case, the results of a bottom-up approach, as followed in this study, should be interpreted separately and not combined with top-down approaches, which already account for all practices in a region, in order to avoid double counting.

The forest modelling as applied in this study is based on steady-state climate conditions, without accounting for changes in CO₂ concentration, nutrient availability, climatic extremes, or disturbances affecting forest carbon stocks. Therefore, the carbon stock accounting results may differ from real-world conditions. Furthermore, for SOC modelling in Yasso, we have used average Finnish meteorological data for different sites in Finland, instead of site-specific data.

The MOTTI stand simulation categorizes harvested wood into sawlogs and pulpwood, allocating the share between these categories solely on the tree's diameter. Therefore, our calculations are based on biomass volume and harvested wood quantity, without considering quality. In this study, only the total volume of wood and corresponding carbon stock was considered, and the subsequent use of the wood products was not taken into account. However, one of the ideas of thinning is to increase the share of large diameter logs used for construction. Wood construction is one way to increase the carbon stocks of products. Therefore, if reduced thinning also reduces the production of wood suitable for construction, that could partly reverse the positive climate impact achieved through reduced thinning. This aspect requires further research.

It should also be noted that the Yasso07 model applies only for mineral soils, so no effect on organic soils is estimated with Yasso07. Furthermore, the Yasso modelling only considers changes in litter input from final felling, while litter inputs during the rotation cycle were assumed to remain constant. The carbon soil emissions from drained organic soils are highly different compared to mineral soils, as the decomposition of peat is the highest source of the soil emissions in Finland (Gerin et al., 2023). However, similarly as in the case of mineral soils, the organic soil emissions can be affected by management, and this also requires further studies.

5. Conclusions

In this study, we have applied a methodological framework that enables the evaluation of GWP_{LULUC} emission and removals of forest products with change in forest management practices. The effect of changes in forest management practices is evaluated by using a bottom-up approach integrating MOTTI forest stand simulation, Yasso soil carbon modelling, and evaluating the GWP_{LULUC} emissions and removal. This approach allows us to evaluate the effects of change in forest management practices. This framework can be applied to diverse contexts such as biofuels, bioelectricity, construction materials, enabling

the calculation of the carbon footprint for each.

Considering the effect of change in management at stand level, GWP_{LULUC} emissions and removals demonstrate variability across regions and vegetation types. No pre-commercial thinning results in GWP_{LULUC} removal in most cases; however, it also results in emissions in some cases, with the total effect being rather negligible. The application of no pre-commercial thinning followed by delayed and heavier thinning considerably improves GWP_{LULUC} removal. The collection of residues leads to a reduction in SOC. However, at the product level, this impact, similarly as the effect of pre-commercial thinning, is rather minimal and does not significantly affect the climate benefits of bio-based products substituting fossil products. Land occupation varies with different species and management practices, and minimizing land occupation for forest production can be considered to have a positive impact on biodiversity. These findings underscore the intricate interplay between regional, species-specific, and change in forest management-related factors in shaping the GWP_{LULUC} emissions and removals of forest-based products. LCA practitioners are therefore suggested to evaluate the GWP_{LULUC} under management changes using species-specific and site-specific data as average data may not accurately capture the actual situation.

For the future research, we suggest performing the simulations and calculating the GWP_{LULUC} for additional plots and locations, as well as assessing additional management practices to evaluate their potential effects.

CRedit authorship contribution statement

Hafiz Usman Ghani: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Anniina Lehtilä:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Anna Forssén:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Xing Liu:** Writing – review & editing, Visualization, Project administration. **Ilkka Leinonen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no competing financial interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2025.10.010>.

References

- Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K., & Väisänen, P. (2019). Forest management recommendations. (In Finnish) Publications of Tapio.
- Akujärvi, A. J., Heikkinen, T., Palosuo, J., & Liski, J. (2014). Carbon budget of Finnish croplands — effects of land use change from natural forest to cropland. *Geoderma Reg.*, 2–3(1–8). doi:<https://doi.org/10.1016/j.geodrs.2014.09.003>.
- Akujärvi, A., Repo, A., Akujärvi, A.M., et al., 2021. Bridging mapping and simulation modelling in the ecosystem service assessments of boreal forests: Effects of bioenergy production on carbon dynamics. *For. Ecosyst.* 8 (4). <https://doi.org/10.1186/s40663-021-00283-2>.

- Ameray, A., Bergeron, Y., Valeria, O., et al., 2021. Forest carbon management: a review of silvicultural practices and management strategies across boreal, temperate, and tropical forests. *Curr. For. Rep.* 7, 245–266. <https://doi.org/10.1007/s40725-021-00151-w>.
- Blatter, C., Eyvindson, K., Hartikainen, M., Burgas, D., Potter, M., Lukkarinen, J., Snäll, T., Torano-Calcioya, A., Mönkkönen, M., 2022. Sectoral policies cause incoherence in forest management and ecosystem service provisioning. *Forest Policy Econ.* 136, 102689. <https://doi.org/10.1016/j.forpol.2022.102689>.
- BSI, 2011. PAS 2050: 2011 Specification for the assessment of life cycle greenhouse gas emissions of goods and services. Co-sponsored by Defra, DECC, & BIS. <https://www.en-standard.eu/pas-2050-2011-specification-for-the-assessment-of-the-life-cycle-greenhouse-gas-emissions-of-goods-and-services/>.
- Cajander, A.K., 1949. Forest types and their significance. *Acta For. Fenn.* 56 (5), 7396. <https://doi.org/10.14214/aff.7396>.
- Council of the European Union, 2024. Climate Action: Council and Parliament Agree to Establish an EU Carbon Removals Certification Framework, 20 February. Available at <https://www.consilium.europa.eu/en/press/press-releases/2024/02/20/climate-action-council-and-parliament-agree-to-establish-an-eu-carbon-removals-certification-framework>.
- D'Amato, D., Gaio, M., Semenzin, E., 2020. A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. *Sci. Total Environ.* 706, 135859. <https://doi.org/10.1016/j.scitotenv.2019.135859>.
- Eggleston, H.S. (Ed.), 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama, Japan.
- European Commission, 2021. Commission recommendation on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. Annex I. *Prod. Environ. Footprint Method* 204–305. https://eur-lex.europa.eu/resource.html?uri=cellar:75e0de0f-5e6d-11ec-9c6c-01aa75ed71a1.0019.02/DOC_2&format=PDF.
- European Parliament, (2023). Parliament adopts new carbon sinks goal that increases EU 2030 climate ambition. Retrieved from <https://www.europarl.europa.eu/news/en/press-room/20230310IPR77223/parliament-adopts-new-carbon-sinks-goal-that-increases-eu-2030-climate-ambition>.
- European Union, 2023. Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413>.
- Feitosa, T.B., Fernandes, M.M., Santos, C.A.G., da Silva, R.M., Garcia, J.R., de Araujo Filho, R.N., Fernandes, M.R.M., da Cunha, E.R., 2023. Assessing economic and ecological impacts of carbon stock and land use changes in Brazil's Amazon Forest: a 2050 projection. *Sustain. Prod. Consum.* 41, 64–74. <https://doi.org/10.1016/j.spc.2023.07.009>.
- FMI, 2024. Vuositilastot. Finnish Meteorological Institute. Retrieved from <https://www.ilmatiiteenlaitos.fi/vuositilastot>.
- Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Bakker, D.C.E., et al., 2023. Global carbon budget 2023. *Earth Syst. Sci. Data* 15 (12), 5301–5369. <https://doi.org/10.5194/essd-15-5301-2023>.
- Gerin, S., Vekuri, H., Liimatainen, M., Tuovinen, J.-P., Kekkonen, J., Kulmala, L., Laurila, T., Linkosalmi, M., Liski, J., Joki-Tokola, E., Lohila, A., 2023. Two contrasting years of continuous N₂O and CO₂ fluxes on a shallow-peated drained agricultural boreal peatland. *Agric. For. Meteorol.* 341, 109630. <https://doi.org/10.1016/j.agrformet.2023.109630>.
- Ghani, H.U., Ivesniemi, H., Leinonen, I., Ruuttunen, K., Khan, M.M.H., Oinas, P., Anttila, P., 2025. Evaluating sawdust-based bioethanol and pyrolysis products in the European Union: feedstock availability, life cycle assessment, and techno-economic analysis. *Environ. Impact Assess. Rev.* 115, 108035. <https://doi.org/10.1016/j.eiar.2025.108035>.
- Haikarainen, S., Huuskonen, S., Ahtikoski, A., Lehtonen, M., Salminen, H., Siipilehto, J., Korhonen, K.T., Hynynen, J., Routa, J., 2021. Does juvenile stand management matter? Regional scenarios of the long-term effects on wood production. *Forests* 12, 84. <https://doi.org/10.3390/f12010084>.
- Hansen, R.N., Eliassen, J.L., Schmidt, J., Andersen, C.E., Weidema, B.P., Birgisdóttir, H., Hoxha, E., 2024. Environmental consequences of shifting to timber construction: the case of Denmark. *Sustain. Prod. Consum.* 46, 54–67. <https://doi.org/10.1016/j.spc.2024.02.014>.
- Hynynen, J., Salminen, H., Ahtikoski, A., Huuskonen, S., Ojansuu, R., Siipilehto, J., Lehtonen, M., Rummukainen, A., Kojola, S., Eerikainen, K., 2014. Scenario analysis for the biomass supply potential and the future development of Finnish forest resources. In: Working Papers of the Finnish Forest Research Institute, vol. No. 302. Finnish Forest Research Institute, Vantaa, Finland. <http://urn.fi/URN:ISBN:978-951-40-2487-0>.
- Hynynen, J., Salminen, H., Ahtikoski, A., Huuskonen, S., Ojansuu, R., Siipilehto, J., Lehtonen, M., Eerikainen, K., 2015. Long-term impacts of forest management on biomass supply and forest resource development: a scenario analysis for Finland. *Eur. J. For. Res.* 134, 415–431. <https://doi.org/10.1007/s10342-014-0860-0>.
- IPCC, 2006. Chapter 4: Forest land. In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_04_Ch4_Forest_Land.pdf.
- IPCC, 2014. Chapter 2: drained inland organic soils. In: 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. [https://www.ipcc-nggip.iges.or.jp/public/wetlands/pdf/Wetlands_separate_files/WS_Ch2_Drain ed_Inland_Organic_Soils.pdf](https://www.ipcc-nggip.iges.or.jp/public/wetlands/pdf/Wetlands_separate_files/WS_Ch2_Drain_ed_Inland_Organic_Soils.pdf).
- IPCC, 2021. Climate change 2021: the physical science basis. In: Masson-Delmotte, V., et al. (Eds.), Contribution of Working Group I to the Sixth Assessment Report of the IPCC. Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/download/s/>.
- ISO, (2018). ISO 14067:2018(E): Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification. ISO.
- Järviö, N., Henriksson, P.J.G., Guinée, J.B., 2018. Including GHG emissions from mangrove forests LULUC in LCA: a case study on shrimp farming in the Mekong Delta, Vietnam. *Int. J. Life Cycle Assess.* 23, 1078–1090. <https://doi.org/10.1007/s11367-017-1332-9>.
- Lehtilä, A., Ghani, H.U., Liu, X., Palosuo, T., Tuomisto, H.L., Leinonen, I., 2025a. Framework for including national-level LULUC emissions and removals in the GWP of agricultural and forestry products in LCA. *J. Clean. Prod.* 494, 144999. <https://doi.org/10.1016/j.jclepro.2025.144999>.
- Lehtilä, A., Ghani, H.U., Liu, X., Forsén, A., Leinonen, I., 2025b. Land use and land use change emissions of forest land in Finnish provinces—an LCA dataset. *Int. J. Life Cycle Assess.* 30 (8), 896–905. <https://doi.org/10.1007/s11367-025-02456-5>.
- Leinonen, I., 2022. A general framework for including biogenic carbon emissions and removals in life cycle assessments for forestry products. *Int. J. Life Cycle Assess.* 27 (8), 1038–1043. <https://doi.org/10.1007/s11367-022-02086-1>.
- Luke, (2023). Forest Statistical Yearbook 2022. Publications of the Natural Resources Institute Finland. <https://urn.fi/URN:ISBN:978-952-380-584-2>.
- Luke, 2024. Maankäyttösektorin ilmastosuunnitelman skenaariotarkastelun päivitys. *Luonnonvara- ja biotalouden tutkimus*, 4/2024. Luonnonvarakeskus, Helsinki. <https://jukuri.luke.fi/items/8cb694b1-797e-4c33-9591-4bb238b38d85>.
- Luke. (n.d.). Luke's MOTTI software predicts the future development of forests. Retrieved from <https://www.luke.fi/en/services/luke-motti-software-predicts-the-future-development-of-forests>.
- Maierhofer, D., van Karsbergen, V., Potrč Obrecht, T., Mendes Saade, M.R., Gingrich, S., Streicher, W., Erb, K.-H., Passer, A., 2024. Linking forest carbon opportunity costs and greenhouse gas emission substitution effects of wooden buildings: the climate optimum concept. *Sustain. Prod. Consum.* 51, 612–627. <https://doi.org/10.1016/j.spc.2024.08.021>.
- Mäkelä, A., Minunno, F., Kujala, H., Kosenius, A.-K., Heikkinen, R.K., Junttila, V., Peltoniemi, M., Forsius, M., 2023. Effect of forest management choices on carbon sequestration and biodiversity at national scale. *Ambio* 52, 1737–1756. <https://doi.org/10.1007/s13280-023-01932-1>.
- Mäkipää, R., Tapio, L., Alexander, K., Mäkelä, A., 2015. Mitigation of climate change with biomass harvesting in Norway spruce stands: are harvesting practices carbon neutral? *Can. J. For. Res.* 45 (2), 217–225. <https://doi.org/10.1139/cjfr-2014-0120>.
- Mäkipää, R., Abramoff, R., Adamczyk, B., et al., 2023. How does management affect soil C sequestration and greenhouse gas fluxes in boreal and temperate forests? – a review. *For. Ecol. Manage.* 529. <https://doi.org/10.1016/j.foreco.2022.120637>.
- Metsäkeskus. (2023). Tietoa Kemera-tuista. Retrieved from <https://www.metsakeskus.fi/fi/metsatalouden-tuet/kemera-tuet/tietoa-kemera-tuista>.
- Puuinfo. (n.d.). Species of trees. Retrieved from <https://puuinfo.fi/puutiето/finnish-forests/species-of-trees/?lang=en>.
- Semenchuk, P., Plutzer, C., Kastner, T., Dullinger, S., et al., 2022. Relative effects of land conversion and land-use intensity on terrestrial vertebrate diversity. *Nat. Commun.* 13 (1), 615. <https://doi.org/10.1038/s41467-022-28245-4>.
- Statistics Finland, 2023. National Inventory Report (NIR) 2023. United Nations Framework Convention on Climate Change. <https://unfccc.int/documents/627718>.
- Tapio. (2023). Best Practices for Sustainable Forest Management. Retrieved from <http://www.tapio.fi/wp-content/uploads/2024/01/Best-Practices-for-Sustainable-Forest-Management-all-slides-18.12.2023.pdf>.
- Tuomi, M., Thum, T., Järvinen, H., Fronzek, S., Berg, B., Harmon, M., Trofymow, J.A., Sevanto, S., Liski, J., 2009. Leaf litter decomposition—estimates of global variability based on Yasso07 model. *Ecol. Model.* 220 (23), 3362–3371. <https://doi.org/10.1016/j.ecolmodel.2009.05.016>.
- UNECE, 2010. Forest Product Conversion Factors for the UNECE Region (Geneva Timber and Forest Discussion Paper 49), United Nations Economic Commission for Europe & Food and Agriculture Organization of the United Nations. https://www.researchgate.net/publication/261212246_FOREST_PRODUCT_CONVERSION_FACTORS_FOR_THE_UNECE_REGION.
- UNFCCC, 2023. National Inventory Submissions 2023. United Nations Framework Convention on Climate Change. <https://unfccc.int/ghg-inventories-annex-i-parties/2023>.