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Research article

Global forest carbon leakage and substitution effect potentials: The case of the Swedish forest sector

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A R T I C L E   I N F O

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A B S T R A C T

The forest sector's climate change mitigation depends on forest carbon sequestration, storing carbon in wood products, and avoidance of fossil greenhouse gas emissions by replacing more emission intensive products or energy sources, i.e., the substitution effect. In addition, market responses to changes in wood supply following altered forest management by one region induce climate relevant changes in form of compensatory roundwood harvest outside the region, and thus forest carbon leakage. This study presents a global climate change mitigation assessment of the forest sector, accounting for market-effects leakage. We use a global forest sector model, wood flow analysis and life cycle inventory data to assess the impact of forest management changes on climate change mitigation, with a focus on Sweden. Results suggest decreased wood harvesting causes global net climate change mitigation until 2070, despite forest carbon leakage, forgone wood product carbon storage and forgone substitution effect potentials. Increasing domestic wood removals induces global additional emissions until 2100. Additional domestic wood product consumption is climate beneficial which however depends on substitution effects actually materializing. Roundwood harvest leakage ranges from 40 % to 60 % and forest carbon leakage from 50 % to 80 %. Leakage effects occur mainly in North America and Asia, with a gradual shift towards Latin America over time. To further the climate benefit, drivers of growing demand should be addressed and measures be implemented which promote more efficient and sustainable use of wood as a resource. Only concerted global forest policy cooperation would avoid leakage and with that result in improved global climate change mitigation.

1. Introduction

The forest sector can mitigate climate change by sequestering carbon dioxide (CO_2) from the atmosphere and storing it as biogenic carbon as well as by substituting wood for materials and energy sources that emit more greenhouse gases (GHG) (EC, 2021a). However, there is a trade-off between augmented harvested wood product (HWP) carbon pools and wood-based substitution on the one side and decreased forest carbon sequestration - through increased harvests - on the other, and vice versa, see, e.g., Seppälä et al. (2019), Hurmekoski et al. (2023), Jonsson et al. (2021), or Soimakallio et al. (2021).

Further, to assess global climate effects of altered forest management confined to a specific geographical area, it is necessary to account for the phenomenon of market-effects leakage. In the context of the forest sector, market-effects leakage entails roundwood harvest leakage and ensuing forest carbon leakage, (i.e., emission displacement). This is when actions to reduce harvest (and thus increase forest carbon sinks) in one region indirectly create incentives for third parties to increase harvests (and thus decrease forest carbon sinks) elsewhere (Aukland et al., 2003). Leakage is caused by a shift in market equilibrium, as forest-conservation projects aiming to increase the forest carbon sink reduce local timber supply, leading to increases in market prices for timber and wood-based products with ensuing pressures on forests outside the project area (Schwarze et al., 2002). However, an increase in timber supply confined to a particular geographical area is likewise susceptible to market-effects leakage, leading to the opposite effect, i.e.,

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potentially reducing harvest pressures outside the area in question, see, e.g., Kallio and Solberg (2018). Consequential forest carbon leakage estimates range from −10 % to 100 % with a mean of about 40 % (Pan et al., 2020; Daigneault et al., 2023).

Several policy initiatives in the European Union (EU), such as the legally binding Nature Restoration Law and the EU Forest Strategy for 2030, recognize the need to protect and enhance the quality of forest ecosystems to improve carbon sequestration and strengthen resilience against the climate and biodiversity crisis (EC, 2021b; EU, 2024). This happens against the backdrop of declining forest carbon sinks across EU Member States (Korosuo et al., 2023), moving away from Land Use, Land Use Change, and Forestry (LULUCF) sector targets which require the sink to increase from 236 Mt CO_2 eq year^{-1} in 2022 (EEA, 2024) to 310 Mt CO_2 eq year^{-1} by 2030 at the EU-level. The implementation of such policies may alter harvesting rates across member states and lead to leakage effects (Di Fulvio et al., 2025).

Within the EU, Sweden hosts the largest forest area (EUROSTAT, 2023a) and accounts for the second largest roundwood production (EUROSTAT, 2023b). The country accounts for only one percent of the global forest area but 4 % of global wood production, and it is the 4th largest wood product exporter (Swedish Forest Industries, 2022). About 80 % of the wood products manufactured in Sweden are exported (SFI, 2024). This makes the issue of market-effects leakage highly relevant for Sweden (compare Kallio & Rannestad (under review)), and the country a pertinent case study.

Two aspects need to be considered simultaneously for a proper analysis of climate implications of changes in forest management: (i) a comprehensive climate assessment of the forest sector, distinguishing the climate effect of forest carbon, HWP carbon pool, and fossil emissions from forest value chains and substitution effects, as done, e.g., for the United States (Dugan et al., 2018), Canada (Moreau et al., 2022), Mexico (Olguin et al., 2018), Japan (Matsumoto et al., 2016), France (Valade et al., 2018), Finland (Hurmekoski et al., 2020; Soimakallio et al., 2016), or Sweden (Lundmark et al., 2014; Skytt et al., 2021; Petersson et al., 2022), and (ii) an analysis of market-effects leakage following forest management changes in the country or region under study, as done by, e.g., Aukland et al. (2003), Murray et al. (2004), Gan and McCarl (2007), Sun and Sohngen (2009), Kallio and Solberg (2018), Schier et al. (2022), or Di Fulvio et al. (2025).

To the best of our knowledge, this simultaneous consideration of both (i) a forest sector's climate change mitigation assessment, and (ii) a global market-effects leakage accounting has not yet been done. In the case of Sweden, Lundmark et al. (2014) has accounted for international trade in the context of a climate change mitigation assessment. However, their findings rest on assumptions of maintaining wood products flows constant over time and across scenarios, while leakage effects were left out of the analysis. Here we try to fill this knowledge gap with the objective to account for both abovementioned aspects (i,ii) in assessing potential global climate change mitigation of the forest sector following changes in forest management at the example of Sweden. In doing so, we provide full account of global implications of national changes in forest management for wood product trade and climate change mitigation. To this end, we couple outcomes of the official Swedish forest impact analysis (Skogliga konsekvensanalyser 2022), in the following "SKA22" (Eriksson et al., 2021) with GLOBIOM-forest (Havlík et al., 2018; Lauri et al., 2021), a partial equilibrium forest sector model, and a wood flow model applying life cycle inventory (LCI) data.

2. Methodology

2.1. Modelling set-up

To address the study's objectives, it is essential to understand (i) national and international forest carbon developments following different domestic wood harvest regimes, (ii) wood use structures as being processed by the domestic forest sector and distributed across a wood product portfolio, (iii) absolute domestic and international demand patterns of wood and wood products, i.e., trade-flows, and finally, (iv) emission profiles of the wood products, as well as their non-wood substitutes.

The modelling sequence of this study is divided into three parts, as depicted in Fig. 1. The geographical scope is global and discriminates between the EU with a Swedish focus on the one side, and the Rest-of-the-World (RoW) on the other side. The time-horizon considered in the study spans over 80 years, i.e., ranging from 2020 to 2100.

The basis and first step of the modelling (Fig. 1) form national Swedish wood harvest and forest carbon scenarios which were taken from SKA22, conducted by the Swedish Forest Agency on behalf of the government of Sweden and in collaboration with the Swedish University of Agricultural Sciences (Eriksson et al., 2022). The SKA22 analyses include the impact on forest condition, biological diversity, forest damage, reindeer husbandry and carbon balance and were conducted using the Swedish forest decision support system Heureka RegWise (Lämås et al., 2023). For our study three different wood harvest and forest carbon scenarios from SKA22 were considered which are further described in Section 2.2.

The second step (Fig. 1) consists of using the national wood harvest projections from the three SKA22 scenarios as input to GLOBIOM (GLOBIOM, 2024). Here we deploy a specialized version of the model, namely GLOBIOM-forest (Lauri et al., 2021). In GLOBIOM-forest, the agricultural sector is simplified, but the forest sector is modelled in greater detail compared to GLOBIOM. GLOBIOM-forest includes forestry, forest industry and bioenergy modules which are described in Lauri et al. (2014, 2017), and Lauri et al. (2019). Wood harvests - constituting the supplied quantity of wood to the domestic and global market – were matched with respective national (SKA22) and global demand scenarios, based on the SSP2-RCP4.5-scenario (IIASA, 2020). In addition, GLOBIOM-forest was used to estimate market-effects leakage in form of roundwood harvest and forest carbon in the Rest-of-the-World as a consequence to changes in domestic forest management in Sweden. In total, six scenarios were modelled using GLOBIOM-forest. These are the three aforementioned SKA22 scenarios, which are accompanied by an alternative version thereof which act as additional 'what-if' scenarios. In these, the domestic demand for wood products in construction was assumed to double by the year 2030 and remain at that level until 2100, referred to "*high domestic demand*" hereafter. A detailed description of GLOBIOM-forest is provided in Section 2.3.

The third step (Fig. 1) consists in integrating the outcome of GLOBIOM-forest, i.e., the projected domestic consumption and exports of wood products and leakage, in terms of its climate change mitigation potential by a wood flow model based on LCI data. This modelling part covers the biogenic carbon balances from forest carbon and HWP carbon storage as well as the fossil GHG emission balance from the value chain of the forest industry and from estimated substitution effects of non-wood products such as concrete, steel, plastics, or fossil energy. The wood flows from harvest volumes to the semi-finished HWPs and to the end-uses, as well as the modelling of the LCI data, are further described in Section 2.4.

2.2. Domestic forest and harvest modelling

The SKA22 scenarios formed the foundation for Swedish wood harvest potentials and forest carbon stocks. These were modelled using the Heureka forest decision support system and were based on Swedish NFI data from 2016 to 2020 (Eggers et al., 2022). Only productive forest land, i.e., forest land where growth is more than 1 m^3 per ha per year was considered for the simulations which extends over a forest area of approximately 23.5 million (M) ha. The remaining 4.6 Mha forest land in Sweden, i.e., unproductive forest land, were not included.

Fig. 2 summarizes the forest increment (gross increment minus natural mortality) and harvest volumes from the SKA22 scenarios which were considered in our study, i.e., a *Business as usual*, *Biodiversity*, and

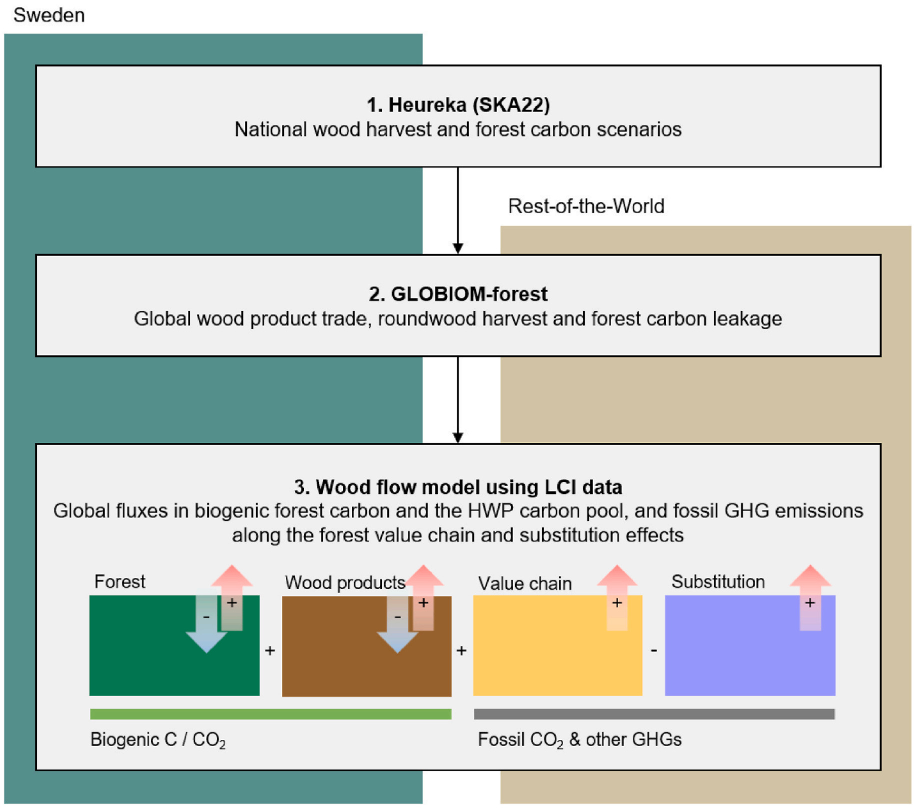

Fig. 1. The study's geographical coverage and modelling steps. First, national wood harvest and forest carbon scenarios from the official forest impact analysis "SKA22" (Sweden), second, integration with the global forest sector model GLOBIOM-forest to analyze wood product trade, roundwood harvest and forest carbon leakage (Sweden, RoW), and third, global accounting of fluxes (sinks in blue, emissions in red) in forest carbon, HWP carbon storage and fossil GHG balances using a wood flow model based on life cycle inventory data (Sweden, RoW). The coloring in green (forest), brown (wood products), yellow (value chain), and purple (substitution) is reappearing in Fig. 8.

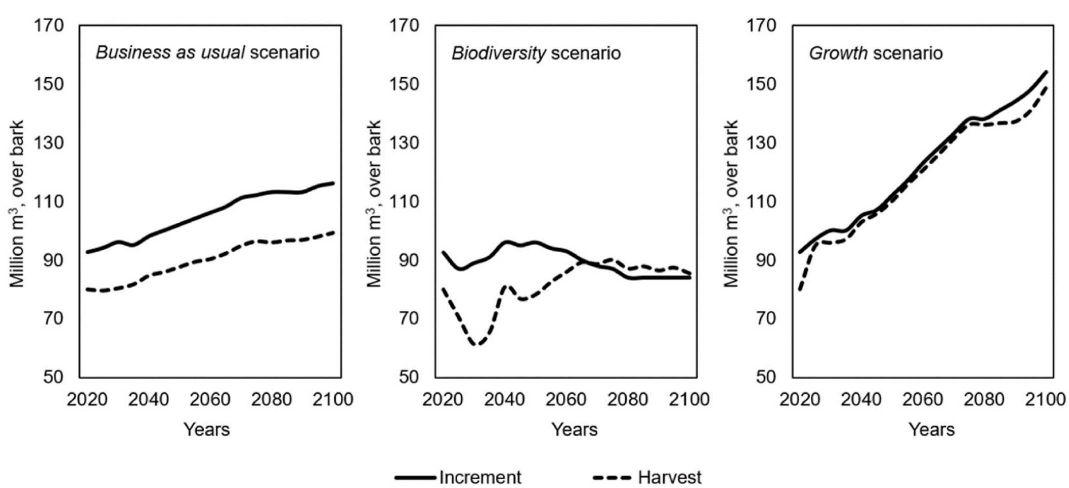

Fig. 2. Projected increment (gross increment minus natural mortality) and harvest volumes of the *Business as usual* scenario, *Biodiversity* scenario, and *Growth* scenario, given for the productive forest land in Sweden, based on SKA22.

Growth scenario (Eriksson et al., 2021). The reference scenario, *Business as usual* (BAU), continues the current forestry practices during the simulated time horizon. This concerns both land use (areas of nature conservation provisions and timber production land), as well as the management methods that are applied today, for example in terms of regeneration methods, choice of tree species and extent of fertilization and clearing. This scenario uses the same felling intensity (felling in relation to increment on timber production land) as in the 2011-2015 period, which corresponds to 79 % on timber production land. In contrast to that, the *Biodiversity* scenario reflects decreased harvest volumes as a result of changed management to favor environmental conservation. The scenario seeks greater diversity in management methods with the aim of providing greater biodiversity and better adaptation to, e.g., reindeer husbandry. In relation to today's forestry, this means that an additional 2.6 Mha will be set aside for nature conservation, that 5.0 Mha of timber production land will be managed using continuous cover forestry, that natural regeneration will be used to a greater extent and that broadleaved tree species will be favored. In areas designated as being of national interest for reindeer husbandry, clearing and thinning regimes promoting ground lichen are applied and non-native tree species are phased out. The “*Growth*” scenario is characterized by efforts to increase tree increment and thereby harvest activity to increase wood production. This is done through increased fertilization, more use of alien tree species and a prioritization of harvesting based on increment rates. Remaining forest properties in the scenarios can be retrieved from Eriksson et al. (2022), and the SKA22 database (SFA, 2023a).

In the Heureka forest decision support system model RegWise which is underlying the SKA22 scenarios, the computation of biogenic carbon in living trees is done using biomass expansion factors. For stump and root biomass they are based on models by Petersson and Ståhl (2006) and for above-stump tree biomass based on Marklund (1988). In young stands, above-ground tree biomass is estimated based on Claesson et al. (2001) and decay of coarse woody debris relies on Kruys et al. (2002) and Sandström et al. (2007). Soil organic carbon in mineral soils relies on the Q-model (Ågren and Hyvönen, 2003) which computes continuous soil organic matter decomposition, and uses emission factors for peatland. In the SKA22 scenarios, soil organic carbon is however assumed to be constant for which the most recent value from the national climate reporting was used (Eriksson et al., 2022). Deadwood carbon is assessed with exponential decay rates from dead wood inflow following tree mortality (Harmon et al., 2000). An RCP4.5 climate scenario is used for all SKA22 forest management scenarios simulated.

2.3. GLOBIOM-forest modelling

2.3.1. Global wood product trade

GLOBIOM-forest is solved recursively for each 10-year period and maximizes the economic surplus defined as the sum from producers and consumers. The supply side of the model is based on a 0.5° spatial grid resolution while the demand side and trade are given for 59 economic regions. The model includes 26 wood-based products. Five harvested products (pulpwood, sawlogs, other industrial roundwood, fuelwood, logging residues) and one non-harvested product (deadwood) are given in the forestry module. In the forest industry module there are four paper and paperboard grades (newsprint, printing and writing papers, packaging materials, other papers), four pulp grades (chemical pulp, mechanical pulp, recycled pulp, other fiber pulp), three mechanical forest industry products (sawnwood, plywood, fiberboard), four forest industry by-products (woodchips, sawdust, bark, black liquor) and two recycled products (recycled paper, recycled wood). Finally, the bioenergy module includes two final products (traditional bioenergy, modern bioenergy) and one intermediate product (wood pellets).

The production capacities from the forest industry and for wood pellets are based on FAOSTAT production data from 2000 to 2020 (FAO, 2023). For the time horizon after 2020 the production capacities develop according to investment dynamics by comparing the current period income and annualized investment costs. The production of the forest industry is modelled by Leontief production technologies which have fixed input-output coefficients. The demand for final products which are included in FAOSTAT statistics is based on respective constant elasticity demand functions that are parametrized by reference volumes, reference prices and elasticity coefficients similar to Buongiorno et al. (2003). Reference prices of the wood products are based on world export prices and transport costs, so that net exporters are based on world prices, and net importers based on world prices plus transport costs (Buongiorno et al., 2003). Reference volumes of the wood products are based on FAOSTAT from the period 2000–2020 (FAO, 2023). After 2020, the reference volumes of wood products are shifted over time based on GDP and population growth in the respective regions. Development of GDP and population is based on the SSP2 “middle of the road” scenario (IIASA, 2020). The elasticity parameters of the demand functions are based on econometric estimates from Buongiorno et al. (2003), Buongiorno (2015) and Morland et al. (2018). Income-elasticities lie between 0 and 1, and are differentiated between low-, middle- and high-income regions. Newsprint, printing and writing papers are assumed to have 0 income elasticity for all regions. Price-elasticities lie between −0.1 and −1. Population elasticity is always 1. The demand for traditional bioenergy (household fuelwood) is assumed to be constant over time due to large uncertainty connected to future development of this product. The demand for final products which are not included in FAOSTAT statistics is based on exogenous data from other models (modern bioenergy) or their demand is generated from semi-finished products use for final products (construction, furniture, wood packaging, textiles).

Wood product trade is modelled by bilateral trade flows. Bilateral trade volumes are based on BACI trade data from 2000 to 2020 (Gaulier and Zignano, 2010). After 2020, trade volumes develop according to trade dynamics that depend on constant elasticity trade-cost functions which are parameterized by historical trade volumes and transport costs. Costs for transport are estimated from the difference between world import and export values (Buongiorno et al., 2003). To facilitate the comparison among the scenarios, imports to Sweden were kept constant among all simulations. The underlying code of the GLOBIOM-forest model including a detailed documentary can be retrieved from Lauri (2023).

2.3.2. Forest carbon leakage modelling

GLOBIOM-forest was initially run for a calibration period of 20 years (2000-2020), during which it was forced to reproduce harvest volumes for this period according to FAOSTAT (FAO, 2023). Afterwards, the model was run recursively until year 2100 in time steps of 10 years. The SKA22 scenarios were implemented after year 2020, i.e. in year 2030. Roundwood harvest and forest carbon leakage were calculated as follows:

$$CL = \frac{\Delta pE^{B}}{-\Delta pE^{A}} \times 100\%$$

where CL represents carbon leakage and Δp changes in carbon emissions E after implementation of a carbon emission mitigation measure or forest policy in a region; $-\Delta pE^{A}$ is the carbon emission reduction in region A with a carbon mitigation measure in place; and ΔpE^{B} is the carbon emission change in region B with no mitigation measure in place (Michalek and Schwarze, 2015).

Market-effects leakage is not a well-defined concept in the case where a forest policy change may occur in a region, but the leakage effect aimed to be analyzed is limited to only a part of that region. Accordingly, when calculating leakage for a country such as Sweden being an EU Member State, two general alternatives exist. The first assumes Swedish forest policy is changed (difference between either *Biodiversity* or *Growth* scenario vs. *BAU* scenario) while other countries, i.e., the Rest-of-the-World, follow a *BAU* forest policy. The advantage of this approach is that the leakage effect can be easily calculated by comparing harvest/carbon changes in Sweden and the Rest-of-the-World. The disadvantage of this approach is that it is unlikely that an EU Member State such as Sweden will change its forest policy independently from the EU. The alternative approach assumes that forest policy in Sweden and the Rest-of-the-EU changes in unison, implying that leakage effects from Sweden to the Rest-of-the-EU would be zero or at least very small. The disadvantage of this approach is that it remains unclear how an EU leakage effect could be divided into that originating from Sweden and the Rest-of-the-EU, respectively. See the Supplementary Material for more detailed information.

In this study, the latter approach is chosen, and the overall EU harvest leakage is split between Sweden and the Rest-of-the-EU by dividing the EU harvest leakage based on the respective shares of harvest difference following the forest policy implementation. This is because it is unlikely that Swedish forest policy differs much from EU forest policy.

2.4. Wood flow and climate impacts modelling

Global wood product trade from GLOBIOM-forest was subsequently used to inform a wood flow model. This served to calculate both HWP carbon storage, and fossil GHG emission balances of the forest value chain and substitution effects. Fig. 3 shows the wood flow from the initial harvest volume over the semi-finished wood product categories to the wood product end-uses and also includes the substituted products. The wood flow from the initial harvest to the semi-finished product level was based on GLOBIOM-forest, as mentioned in Section 2.3.1, and the wood product distribution from the semi-finished level to the end-use level relied either on GLOBIOM-forest, or on Hurmekoski et al. (2023). The assumed substituted products and thus production processes relied entirely on Hurmekoski et al. (2023).

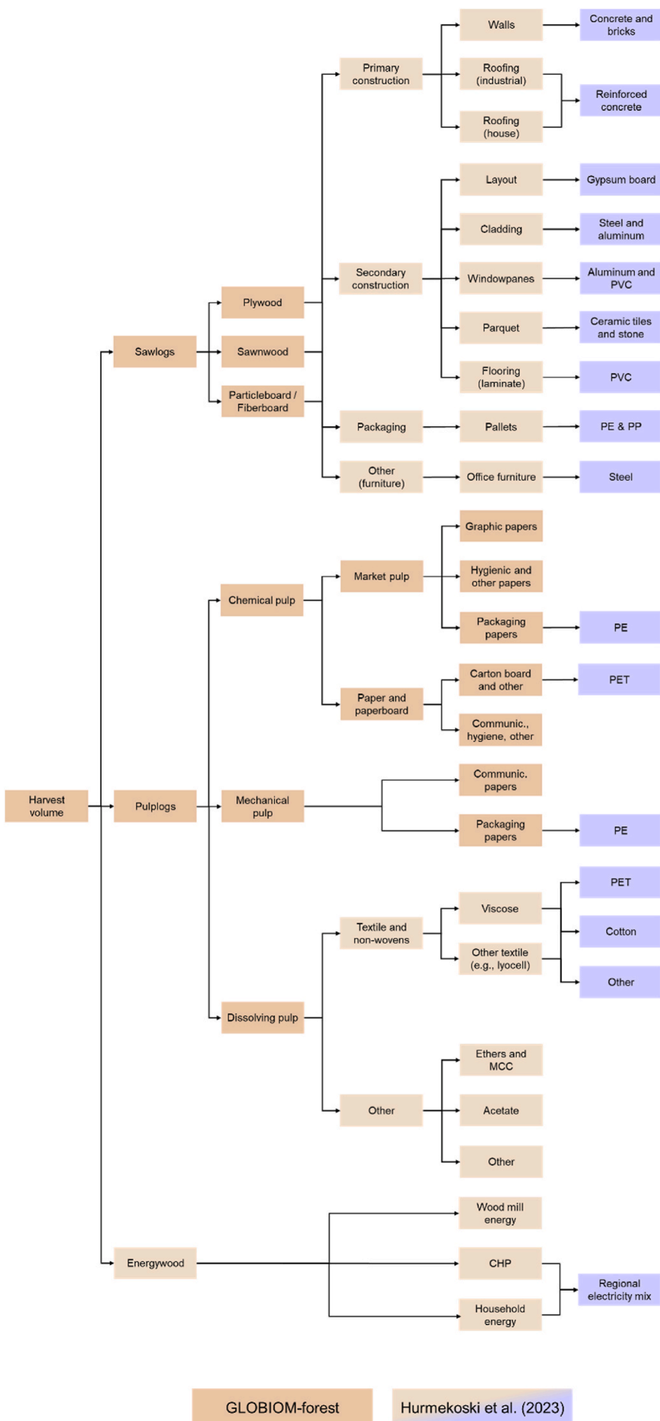

Fig. 3. Wood flows modelled from initial harvest over semi-finished wood products to their end uses, with corresponding substituted products, as based on GLOBIOM-forest or Hurmekoski et al. (2023), respectively.

As to the climate change mitigation assessment (Fig. 1), global balances of biogenic carbon from forests and HWPs were calculated (in form of CO_2), as well as fossil GHGs in form of CO_2, CH_4, and N_2O. In doing so, the global warming potential (GWP_{100}) was used as the climate metric (IPCC, 2021). Both HWP carbon storage potential and the substitution effect potential were calculated based on the final distribution on the wood product end use level. For the assessment of the HWP carbon storage different half-life times for varying wood product categories were applied following the 'production approach' (Rüter et al., 2019). For the estimation of fossil value chain emissions of the wood products, as well as the substitution effect potentials, underlying LCI data relied on the ecoinvent database, version 3.9.1 (Wernet et al., 2016). The LCI data considered the life cycle from "cradle to grave", i.e., from the production of the products to their end-of life. Recycling of wood products was considered indirectly by GLOBIOM-forest. Substitution effects of replacing materials, e.g., concrete and brick avoidance by primary construction wood used in walls, are calculated by subtracting the fossil emissions of the non-wood product from that of the wood product. The substitution effect potentials and value chain emissions were kept constant across the entire time horizon and thus represent recent emission profiles. For details about the LCI data, see the Supplementary Material.

3. Results

3.1. Domestic forest carbon development

All SKA22 scenarios depart from year 2020 with an initial forest carbon sink of −40 Mt CO_2 eq year^{-1} (Fig. 4). The *Business as usual* scenario maintains the forest carbon sink comparatively stable over the time horizon and only decreases moderately to about −33 Mt CO_2 eq year^{-1} by 2100. In contrast, under the *Biodiversity* scenario the forest carbon sink increases substantially in the medium term, doubling around the year 2040 to approximately −80 CO_2 eq year^{-1}. In subsequent decades, however, the sink diminishes, and the annual carbon sequestration drops below −10 Mt CO_2 eq year^{-1} at the end of the time horizon, mainly due to a shift in the forest-age class distribution towards an older forest state. In the *Growth* scenario, the forest carbon sink is the smallest among the three scenarios with an average of −23 Mt CO_2 eq year^{-1}. This is due to the increased harvest volumes which make the sink continuously remain below the initial sequestration rate in 2020.

3.2. Global wood product demand

Irrespective of the scenario, about three times as much wood products are exported in the beginning of the time horizon (2020) compared to domestic consumption (Fig. 5). In the "*high domestic demand*" scenarios, the difference between exports and domestic consumption decreased, compared to the default SKA22 scenarios. In all cases, domestic consumption increases towards the end of the time horizon, based on the trajectory of the underlying SSP2-scenario, while exports decrease, except for the *Growth* scenario where domestic harvest volumes increase more than domestic demand which leads to a higher level of exports. For more detailed information on trade and domestic consumption see the Supplementary Material.

3.3. Global and regional roundwood harvest and forest carbon leakage

The average leakage of forest carbon is found to be always larger than that of roundwood harvest (Fig. 6). Forest carbon leakage ranges from about 50 % to 80 % while roundwood harvest leakage ranges from about 40 % to 60 %. In the *Biodiversity* scenario, forest carbon leakage is

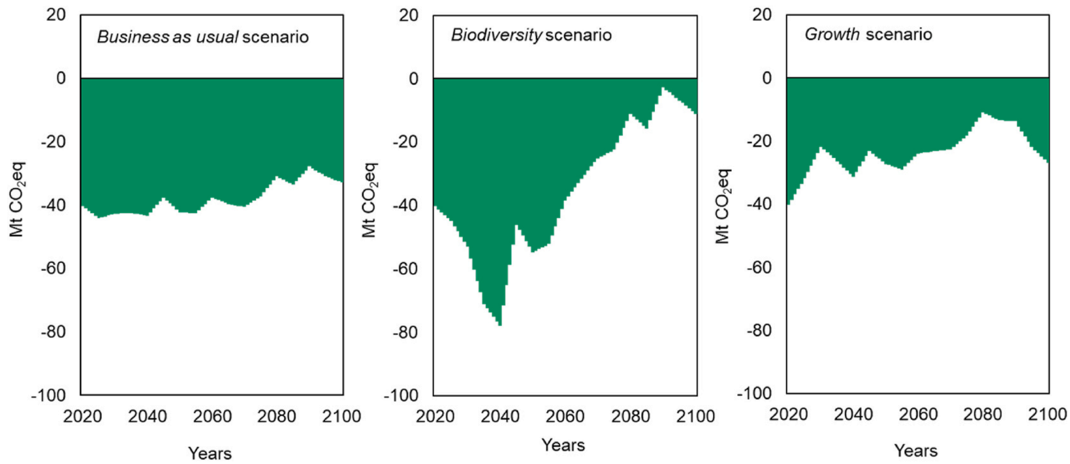

Fig. 4. Annual Swedish forest carbon fluxes for the three different forest management scenarios based on SKA22. Compare with increment and harvest in Fig. 2.

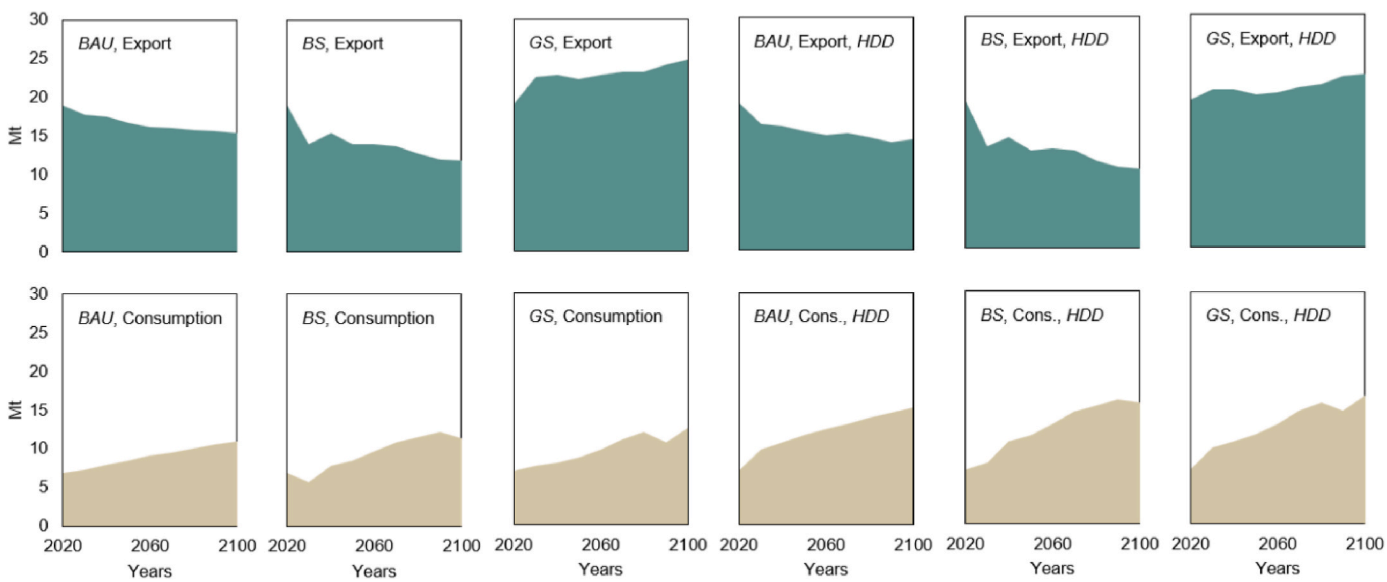

Fig. 5. Simulated wood product demand in the Rest-of-the-World (exports), top row, and in Sweden (consumption), bottom row, given for the forest management scenarios based on SKA22 (*BAU*, *Biodiversity* (*BS*), *Growth* (*GS*)) and the domestic demand variation thereof, i.e., the "*high domestic demand*" (*HDD*) scenario.

highest in the beginning of the time horizon and levels off slightly over time, while roundwood harvest leakage increases to the medium term, and also levels off in the longer term. In the *Growth* scenario, both leakage effects are smallest at the beginning of the time horizon and gradually increase until the medium term, level off slightly afterwards and finally increase again towards the end of the time horizon.

Roundwood harvest leakage initially occurs mostly in North America regardless of the scenario, and shifts in the medium to long term towards Latin America (Fig. 7). Next to that, roundwood harvest leakage takes place in Asia, while only minorly in the region of Former Soviet Union and in Africa. In the case of forest carbon, initial leakage hotspots are North America and Asia for either scenario, while Latin America's share increases towards the end of the time horizon especially under the *Growth* scenario, similar as for roundwood harvest leakage. In parallel, forest carbon leakage in Asia decreases in both scenarios, and North America remains a hotspot for forest carbon leakage, especially in the *Biodiversity* scenario.

3.4. Global climate change mitigation potential

The *Biodiversity* scenario leads cumulatively to a medium-term net climate change mitigation effect compared to the *Business as usual* scenario (Fig. 8) amounting to about 5.0 Gt CO_2 eq until approximately year 2070, but subsequently turns into a net source of GHG emissions of 12.0 Gt CO_2 eq until the end of the projection, i.e., year 2100. The *Growth* scenario leads cumulatively to a net addition of GHG emissions for the entire time horizon of around 13.3 Gt CO_2 eq. For the *Biodiversity* scenario this pattern is due to the combination of forest carbon leakage, i.e., increased harvest in the Rest-of-the-World and resulting decreased forest carbon sequestration, and forgone, i.e., not realized, substitution effects and HWP carbon storage which make the initial climate benefit to switch to the contrary. For the *Growth* scenario net emissions arise because the sum of forest carbon leakage, this time in form of increased carbon sequestration in the Rest-of-the-World, and additional substitution effects as well as HWP carbon storage are not sufficient to offset the loss of domestic forest carbon and additional value chain emissions. Regardless of the scenario, carbon fluxes from domestic forests as well as forest carbon leakage in the Rest-of-the-World dominate the GHG balance. The *high domestic demand* alternatives of both *Biodiversity* and *Growth* scenario increase the net sink effect in each case. In terms of the cumulative annual average, the climate performance of the *Biodiversity* scenario is improved by a factor of 2.8 and that of the *Growth* scenario by

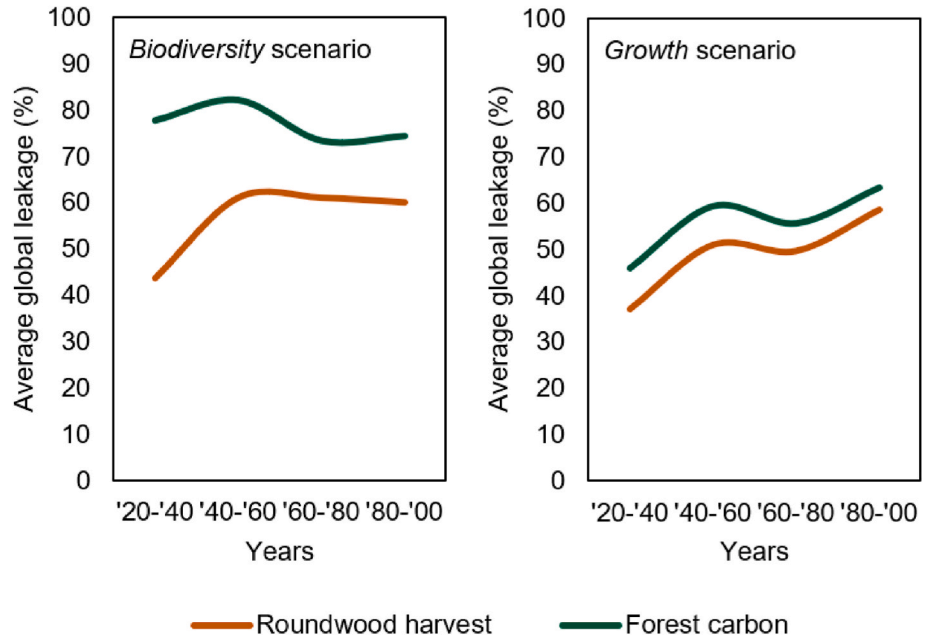

Fig. 6. Rolling average of global roundwood harvest leakage and forest carbon leakage of the *Biodiversity* scenario and *Growth* scenario, respectively.

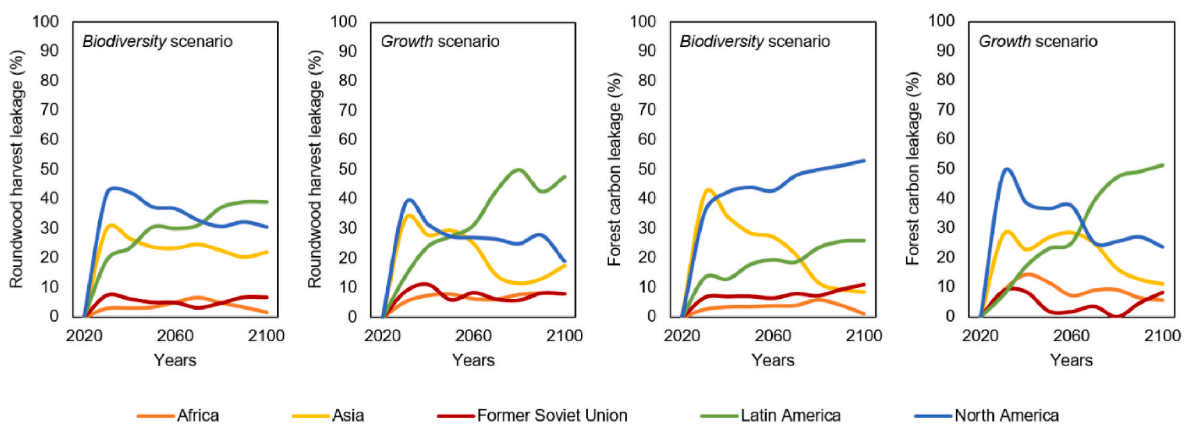

Fig. 7. Relative regional shares of global roundwood harvest leakage (left charts) and forest carbon leakage (right charts) of the *Biodiversity* scenario and *Growth* scenario, respectively.

a factor of 1.2. The reason for that are increased domestic HWP carbon storage and higher domestic substitution effects.

4. Discussion

4.1. Global climate change mitigation potential

The results of our study suggest that a shift towards decreased domestic wood harvesting (*Biodiversity* scenario) leads to climate change mitigation until 2070, despite less HWP carbon storage and substitution effect potentials, as well as forest carbon leakage occurring in the Rest-of-the-World, and subsequently turns into a net source of emissions. This outcome originates majorly from a change in the forest age class distribution under the *Biodiversity* scenario, as compared to the *Business as usual* scenario and is based on a comparable initial forest carbon sink (−40 Mt CO_2 eq year^{-1}) to that of the reported LULUCF forest sink for Sweden in the same year, −37 Mt CO_2 eq year^{-1} (SEPA, 2023). This forest carbon sink is mainly driven by growth in living tree biomass while carbon fluxes in deadwood and soil organic carbon play only a marginal role. Our results further suggest that increasing domestic forest management intensity (*Growth* scenario) leads to net additions of GHG emissions over the entire time horizon until 2100 as additional HWP carbon storage and substitution effects together with net increases in forest carbon in the Rest-of-the-World do not offset the loss of domestic forest carbon. This outcome is in line with the conclusion of a great body of literature studying climate change mitigation potentials of forest management changes, i.e., that intensifying the forest use would not induce climate-change mitigation in the short to medium term, see, e.g., Matsumoto et al. (2016), Skytt et al. (2021), Moreau et al. (2022), Soimakallio et al. (2021), Schulte et al. (2022), Rummukainen (2024), or Englund et al. (2025). For the case of Sweden, decreasing forest use intensity seems advisable, first in order to approach towards the legally binding targets set forward by the EU Nature Restoration Law (EU, 2024), and second, because the margin between gross annual increment minus natural mortality and annual harvests has lately been the smallest since 1975, which offered space for only about additional 2-3 Mm^3 of harvest (SCB, 2025). This development stands against the backdrop of a past century of increasing Swedish forest growth and forest carbon sequestration, which has however abruptly decreased over the last decade, with climate-related drought being the most likely cause (Laudon et al., 2024).

The *high domestic demand* versions of either *Biodiversity* or *Growth*

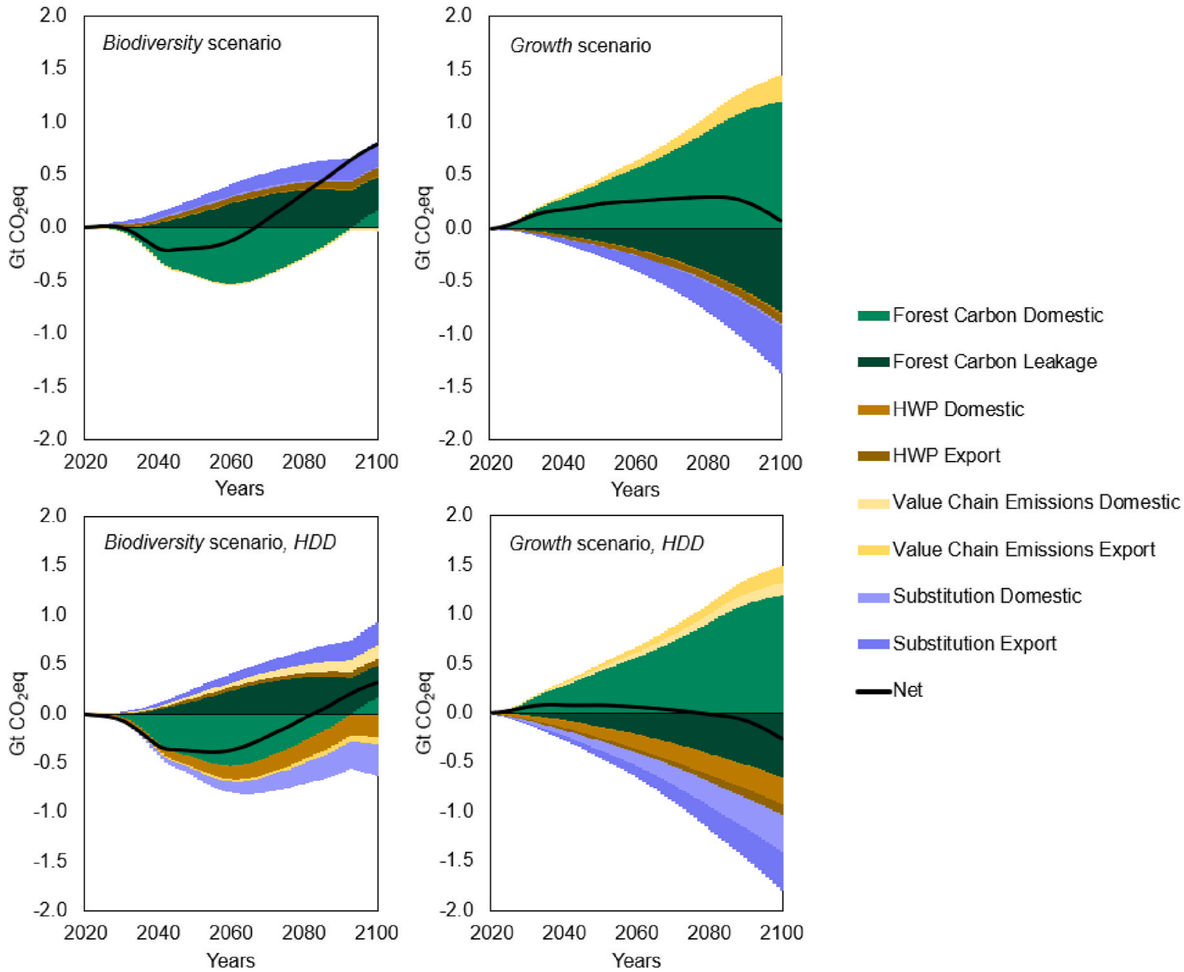

Fig. 8. Cumulative climate change mitigation potential of the *Biodiversity* and *Growth* scenario, as well as the *high domestic demand* alternatives, as compared to the *Business as usual* (BAU) scenario. Note that positive values indicate net emissions and negative values net sequestration.

scenario simulate doubling domestic demand for wood products in construction and were climate beneficial in both cases. These 'what-if' alternatives to the scenarios highlight the hitherto vast demand-side growth potential for timber use in construction which in terms of raw material consumption in the construction sector at the EU-level still remained at only 1 % in 2017, while the remaining 5 % were metal-ores, and 93 % dominance by non-metallic minerals (concrete) (Trinomics, 2021). This pattern is similar, yet less strongly pronounced in Sweden. Here, 77 % of the projected dwelling demand is foreseen to be met by multi-family housing construction in which timber-frame use in 2019–2020 accounted for 19 % (Malmqvist et al., 2021; SCB, 2022), thereby also leaving large potential for increased wood product use to exhaust increased HWP carbon storage and substitution effects. Meanwhile an associated increase in domestic sawlog supply following a total timber-frame use in Swedish multi-family housing construction would constitute approximately 1 % of the annual sawlog harvest only (Schulte et al., 2023).

Indeed, fostering demand-side policies in order to increase the stock of long-lived HWPs and thus obtain related substitution benefits has been recommended before to enhance climate change mitigation via the forest sector (see, e.g., Kallio and Solberg, 2018). However, this increased climate benefit is heavily dependent on the assumption that an increased domestic demand (more consumption of wood products) would actually lead to additional substitution effects. If the substitution effects in general do not materialize as estimated in our study, a more intensive domestic forest harvest (*Growth* scenario) would perform more detrimental for global climate change mitigation as indicated here. In parallel, other studies point out that decreasing consumption leads to a stronger climate benefit than increasing consumption (Vogel and Hickel, 2023; Kallis et al., 2025). In that context, the neoclassical economic theory underlying integrated assessment models and partial equilibrium models such as GLOBIOM, is perceived a general limitation for simulating a broad variety in possible climate change mitigation avenues of society as the models often only insufficiently account for alternative economic developments, such as post-growth or sufficiency (Kallis et al., 2025).

4.2. Global leakage effects

4.2.1. Roundwood harvest and forest carbon leakage

Our simulated roundwood harvest leakage as a consequence of changes in Swedish forest management ranges from about 40 % to 60 % in the Rest-of-the-World. This level of leakage is in line with Lundmark (2025) who indicates roundwood harvest leakage to range between 24 % and 77 %. Moreover, our roundwood harvest leakage is smaller than that estimated by Kallio and Solberg (2018) being 79 %, and at the lower end of those estimates from Kallio and Solberg (2018) to range between 60 % and 100 %, and those of Kallio & Rannestad (under review) with a leakage rate of 67 %. Di Fulvio et al. (2025) found that for every cubic meter reduction in harvest, the Rest-of-the-World will increase its harvest by up to 0.79 m^3. However, they further show that the leakage will decrease over time. Accordingly, the roundwood harvest leakage found in our study is a comparable estimate when benchmarked with other studies. Differences in the leakage outcomes among the studies could be due to differing assumptions as to the actual forest management changes underlying the modelled scenarios.

Although a similar harvest leakage can occur in different regions, this may not imply similar rates of forest carbon leakage. Our results suggest that forest carbon leakage in the Rest-of-the-World is larger than the roundwood harvest leakage. Across an average over both *Biodiversity* and *Growth* scenario and over the entire time horizon, the forest carbon leakage is 27 % larger than the roundwood harvest leakage. This effect can be explained by differences in regional forest management, age-class distribution, biomass growth curves and mortality. For example, when compared to the domestic forest management in Sweden which is characterized by intensive forestry (Scherpenhuijzen et al., 2025) a less efficient forest management is given in the Rest-of-the-World, such as in form of an older age-class distribution or higher harvest losses.

4.2.2. Regional distribution of leakage

Regarding the geographical distribution of roundwood harvest leakage, the results of our study are in line with Kallio and Solberg (2018), Schier et al. (2022), Kallio & Rannestad (under review) and Di Fulvio et al. (2025), who conclude that the sum of the boreal region (here North America + Former Soviet Union) absorbs most of the leakage, followed by Latin America, and Asia. This pattern may be explained by that changes in Swedish forest management impact foremost coniferous wood which is, until today, mostly substituted by alternative coniferous wood being found in similar boreal latitudes in North America. However, over time, Swedish domestic production and especially the chemical pulp making industry faces a decreasing relative competitiveness in the global wood product market, reflecting tropical short rotation plantations replacing wood supply from boreal zone long rotation semi-natural forests (Lauri et al., 2021). Since the domestic forest industry heavily relies on pulp product exports - as recognizable in the large (forgone) substitution effect potential created by exports from pulp products in the default scenario versions (Fig. 8) - there exists the possibility to lose not only market shares, but also the potential for substitution effects from replacing emissions intensive products and energy sources. A major driver influencing these developments is the assumption that global wood product demand increases, primarily in Asia. The low leakage in the remaining global regions, namely Africa and the Former Soviet Union, may be explained, first by low substitutability of the wood originating from these regions (Africa), or second, due to limited trade relations (Former Soviet Union).

An increasing geographical leakage occurrence in tropical regions characterized by more carbon-dense or biodiversity-rich forest ecosystems can mean worse performance in indicators associated with both direct and indirect risks of biodiversity degradation, e.g., forest governance, or the protection status of red-listed species (Fischer et al., 2023; Kallio & Rannestad under review). A planned expansion of conservation areas in EU forest policies could thus risk to increase biodiversity degradation globally. This trend may be intensified if similar forest conservation measures were implemented in North America alongside those in the EU, which would let harvests in the EU decrease less at the expense of that biodiversity-rich tropical countries would face even greater pressure for intensified harvests (Kallio & Rannestad under review). The results of Rosa et al. (2023) suggest that expanding set-aside areas to more than 25 % of the EU's currently managed forest land by 2100 increases the global extinction risk compared to the continuation of current forest management, while a closer-to-nature forest management would start to do so up from a 50 % extension across the EU's forest land. As mentioned above, this outcome stems from a projected increase in EU forest biomass imports, partially from biodiversity-vulnerable regions to compensate for the decrease in domestic harvest. The SKA22 *Biodiversity* scenario of the present study could imply comparable outcomes because it entails additional 2.6 Mha set aside areas, and conversion of 5.0 Mha towards continuous cover forestry. Quantifying the associated biodiversity leakages outside Sweden was however out of scope of our study as its focus lies on the climate change mitigation impacts.

Policymakers should consider this when designing conservation and trade policies. In this context, also the EU regulation on deforestation-free products (EUDR) may have only limited impact, as the highest growth in demand for wood products is developing outside the EU, and the EU can only directly regulate wood products entering or leaving its own territory. More attention should thus be given to addressing the drivers of growing demand. In addition, policy measures should promote a more efficient and sustainable use of wood resources because a substantial portion of EU wood harvests is still used for energy generation, or short-lived wood products only (Cazzaniga et al., 2022; Bozzolan et al., 2024), despite the availability of alternative renewable energy sources and acknowledged climate benefits from extended use of long-lived wood products, e.g., in construction (Churkina et al. 2020).

4.2.3. Leakage effects' impact on the forest sector's climate change mitigation

To the best of our knowledge, linking global roundwood harvest leakage effects to global carbon dynamics of forests, HWPs, and GHG emissions of the forest value chain and substitution effects, has not been done before to the extent given here. For Sweden only Lundmark et al. (2014) has accounted for international trade in the context of a climate change mitigation assessment of the forest sector. In their study, static wood product flows over time and excluding leakage effects from of the analysis lead to the result that the largest climate change mitigation potential of the domestic forest sector lies outside Sweden, chiefly due to large substitution effects from exported wood products. This outcome is not supported by the results of our study which instead suggest that the forest carbon fluxes in domestic forests as well as those in the Rest-of-the-World caused by roundwood harvest leakage have the largest climate role. This difference in results can be attributed to a more elaborated dynamic modelling of international supply and demand patterns of wood products, updated fossil GHG emission data used for estimating the substitution effects, and, importantly, the accounting for leakage effects. Accordingly, our study advances the so far scarce understanding of the impact of market-effects leakage on the overall climate change mitigation potential of the forest sector. As such, our results may, for example, give insights on the general climate effectiveness of investments in the forest sector, for example, in terms of voluntary carbon markets (Daigneault et al., 2023). Forest carbon leakage can act as a break-even point for a forest sector's globally effective net climate change mitigation when considered jointly with changes in domestic forest carbon, HWP carbon, and fossil GHG balances. This is as the forest carbon leakage can turn a seemingly climate beneficial domestic forest management shift into a global net addition of GHG emissions, and vice versa. In our study, this could have occurred if the forest carbon leakage had been larger, e.g., by roundwood harvest leakage continuously occurring in tropical instead of boreal regions. To indicate a precise threshold level of roundwood harvest or forest carbon leakage which may undermine global mitigation is however difficult. This is because of the non-linear forest carbon dynamics in both, the domestic forests as well as those in which forest carbon leakage may occur.

Climate-relevant leakage effects can however not only occur in terms of forest carbon, i.e., within the same sector, but also across sectors. Such cross-sectoral leakage occurs if, for example, the country or region under study decreases harvests, and hence 'forgone' HWP carbon storage and 'forgone' substitution effects arise. Due to international trade, another region, such as, North America, could increase harvests, so that finally the leakage in terms of the 'forgone' HWP carbon and substitution effect is decreased, resulting in a 'net' effect. This effect is accounted for in our assessment in form of the global net change in HWP carbon and substitution effect (Figs. 1 and 8) while the 'gross' leakage across the bilateral balance between countries or regions is inherently accounted for in the international trade simulated by GLOBIOM-forest. An alternative way of accounting for such cross-sectoral leakage would require the assessment via a general equilibrium model in addition to that of a partial equilibrium model (Pan et al., 2020). By that, leakage towards the agricultural sector, e.g., in the form of increased reliance on bioenergy crops, could also be assessed. In fact, Pan et al. (2020) highlight that ignoring the impact of agriculture expansion/land use change on the contributions of forestry conservation policies may overestimate the actual leakage ratio by about 41 %. The application of a general equilibrium model was however out of the scope of our study. It should therefore be highlighted that only concerted international forest policy with harmonized forest management would avoid market-effects leakage of any kind and with that result in net global climate change mitigation.

4.3. Uncertainties and limitations

The global accounting of fossil GHG emissions in a climate change mitigation assessment of the forest sector depends to a great extent on the geographical level of detail and consistency of LCI data. In our study the LCI data used relied on average emission profiles on the European and Rest-of-the-World level, due to insufficient data availability for a more nuanced regional discrimination (Wernet et al., 2016). If more detailed and tenable LCI data had been available, this would have improved the alignment of our modelled GHG emissions with that of the official GHG emission reporting under the United Nations Framework Convention on Climate Change (UNFCCC). This inconsistency was however accepted as a compromise in order to keep a consistent data source for the LCI emission profiles of both, the forest industry and the non-wood industries.

Modelling forest developments under climate change is further connected to uncertainty. In terms of the Heureka forest decision support system, this is expressed, e.g., by insufficient consideration of forest disturbances which would compromise the forest increment patterns used here. The estimates used from the SKA22 may thus be over-optimistic since mainly forest growth enhancing factors from climate change are accounted for in Heureka (Eggers et al., 2022). Accordingly, an improved forest disturbance consideration could yield differences as to the forest carbon sink following different forest management types, e.g., in form of increased storm resilience under extended continuous cover forest management (Hanewinkel et al., 2014, SFA, 2023b).

The possibility for two modelling alternatives as to estimating market effect leakage create additional uncertainty. This is because Sweden is part of the EU, a supranational political and economic union. In the first modelling alternative the forest policy change is only assumed to occur in Sweden, while the Rest-of-the-EU and the remaining Rest-of-the-World is following their baseline forest policies. The advantage of this approach is that leakage effects can be calculated straightforward by comparing the harvest or forest carbon changes in Sweden and the total of the Rest-of-the-World (including the EU). The disadvantage however is that it is unlikely that Sweden, as part of the EU, will change its forest policy towards a less intensive management independently from the EU. Singling out one country from the EU and looking at the leakage thus does more sense if the country is increasing harvest (which is not in line with present EU policy). In the second modelling alternative - which is the one chosen in our study - the forest policy change occurs in Sweden plus the Rest-of-the-EU, while the Rest-of-the-World (excluding the EU) is following its baseline forest policy. This approach is more realistic taking into account that the EU follows a common forest policy, so that leakage between Sweden and the Rest-of-the-EU is zero. The disadvantage of this approach is that it is unclear how to divide the leakage effect occurring in the Rest-of-the-World between Sweden and the Rest-of-the-EU.

Ultimately the recent geopolitical developments affecting international trade of wood products such as the war in Ukraine, or trade tariffs among the United States and the EU and other countries were not accounted for here. Long-term impacts following these situations are uncertain, but could be accounted for in terms of, e.g., changes in imports of roundwood from Russia, and Belarus (Jonsson and Sotirov, 2025), or exports to the United States.

5. Conclusions

This study advances the existing literature on forest-sector climate change mitigation by jointly accounting for (i) global fluxes in forest carbon, HWP carbon, as well as fossil emissions and substitution effects, and (ii) market-effects leakage in terms of roundwood harvest and forest carbon, as a consequence of domestic forest management changes.

Despite the effect of forest carbon leakage, our results suggest that a decrease in domestic forest management intensity, e.g., in form of reduced harvests, yields global net climate change mitigation, for at least until 2070. After 2070, this climate benefit is reversed and the reduction of domestic forest management intensity induces global net emissions. On the contrary, a shift towards more intensive domestic forest management leads to immediate global net emissions until 2100. The underlying forest carbon leakage ranges between 50 % and 80 %, and associated roundwood harvest leakage between 40 % and 60 %, depending on the scenario and point in time between 2020 and 2100. Simulated regional roundwood harvest leakage and forest carbon leakage occurs mainly in North America and Asia with a shift towards Latin America past 2060. Regardless of the scenario, global roundwood harvests are projected to increase, driven by rising demand for wood products. This trend poses significant global risks not only for climate change mitigation, but also biodiversity conservation. Accordingly, we recommend to focus on addressing drivers of growing demand and implementing measures which promote more efficient and sustainable use of wood resources since, still, a substantial proportion of EU wood harvests is used for energy generation and short-lived wood products. Finally, as to the global net climate impact we want to stress that only concerted global forest policy would eliminate market-effects leakage within the forest sector and across sectors, and by that result in real net global climate change mitigation.

CRediT authorship contribution statement

Maximilian Schulte: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Pekka Lauri:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Fulvio Di Fulvio:** Writing – review & editing, Validation, Resources, Conceptualization. **Nicklas Forsell:** Writing – review & editing, Validation, Resources, Conceptualization. **Andrey Lessa Derci Augustynczik:** Writing – review & editing, Validation, Conceptualization. **Jeannette Eggers:** Writing – review & editing, Validation, Resources. **Thomas Hahna:** Writing – review & editing, Validation. **Ragnar Jonsson:** Writing – review & editing, Validation, Investigation, Conceptualization.

Consent for publication declaration

Not applicable.

Ethics and consent to participate declarations

Not applicable.

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Declaration of competing interest

Maximilian Schulte declares that the mutual funding by Swedish University of Agricultural Sciences and Stora Enso AB may be considered as a potential competing interest. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.127193.

Data availability

See Supplementary Material

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