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Exploring trade-offs in forest carbon storage: A cost-effectiveness study of Nordic forests and harvested wood products

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ABSTRACT

Forest-based carbon sequestration plays an important role in climate mitigation, yet strategies vary widely in effectiveness and cost. This study compares two optimization goals in the Nordic forest sector, maximizing carbon in harvested wood products (HWP) and in avoided forest harvest plus HWPs. A partial equilibrium forest sector model (NFSM), combined with the method of Modeling to Generate Alternatives (MGA), is used to assess trade-offs between economic outcomes and carbon storage goals. Marginal abatement cost (MAC) curves are indirectly derived from the results. The analysis shows that maximizing avoided harvest and HWP achieves higher CO_2 gains at substantially lower costs (about €15–463/tCO_2) compared to only maximizing HWP (about €44–1200/tCO_2). In addition, the results reveal that carbon-focused strategies reshape industrial and trade dynamics in opposing ways. Bioeconomy-oriented approaches drive production and exports at higher carbon costs, while conservation-focused strategies reduce harvests and raise the risk of market leakage. These findings highlight the need for integrated policies that reduce reliance on product-based carbon storage while strengthening forest-based sequestration and storage.

1. Introduction

The Nordic forest sector is undergoing a challenging transition as it faces growing expectations to simultaneously supply renewable raw materials and economic value while also acting as a carbon sink to mitigate climate change (European Commission, 2021; Nordic Council of Ministers, 2023; UNECE, 2011). In response, policy debates reveal two increasingly divergent strategies for managing these competing demands. On the one hand, European and Nordic forest policies promote a bioeconomy-oriented approach, encouraging active forest management to supply renewable materials, bioenergy, and biochemicals (Hetemäki and Kangas, 2022; Widmark et al., 2020). This strategy emphasizes fossil substitution while supporting industrial growth. On the other hand, conservation-oriented strategies highlight the role of forests as long-term carbon sinks through reduced harvesting, extended rotation periods, and protection of high-carbon stock forests (Chiti et al., 2024; Framstad et al., 2013; Lundmark et al., 2018; Mäkelä et al., 2023). These approaches caution against over-reliance on substitution effects, pointing to delayed carbon payback, potential carbon debt, and risks to biodiversity and ecosystem resilience under intensive forest use (Bentsen, 2017; Holtsmark, 2012; Soimakallio et al., 2022). Trade-offs are especially evident when balancing these conflicting objectives in the Nordic countries (Hynynen et al., 2025), especially with their well-developed forest-based bioeconomy and policy-emphasized climate neutrality goals (European Commission, 2023; Nordic Council of Ministers, 2023).

Within this context, forests and harvested wood products (HWPs) offer complementary but competing carbon functions. Forests accumulate CO_2 in standing biomass and soils, whereas HWPs extend storage after harvest, particularly through long-lived products like construction materials. Shorter-lived products, such as paper, provide less durable storage (IPCC, 2006). HWPs may also deliver substitution benefits (Howard et al., 2021; Leskinen et al., 2018; Myllyviita et al., 2021), though their effectiveness depends on sustained harvest and production, raising concerns about biodiversity and long-term resilience (Favero et al., 2020). The fundamental policy challenge is therefore not simply to maximize one carbon pool, but to evaluate the relative costs, benefits, and trade-offs between these two mitigation pathways.

A key tool for addressing such trade-offs in climate economics is the marginal abatement cost curve (MAC), which measures the additional cost of reducing or storing one more ton of CO_2. Initially developed in the energy and industrial sectors (Huang et al., 2016), MACs have since

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been applied to land use and forestry, reflecting the growing recognition of forests as cost-competitive mitigation options (Kindermann et al., 2008; Strengers et al., 2008). Empirical work confirms that forest-based sequestration often compares favorably with energy-sector mitigation. For example, Liu et al. (2022) find afforestation in Taiwan costs $35–65/t$CO_2$, and Deng et al. (2022) show forest management responds strongly to carbon prices. These benchmarks underscore the importance of accurately estimating carbon storage costs when designing forest-sector policies. MACs in forestry have been represented through various valuation metrics—market carbon prices (e.g., EU ETS at ~€65/tCO_2), social cost of carbon (mean ~ $55/t$CO_2$; Wang et al., 2019), and shadow prices from forest optimization models (Sohngen and Mendelsohn, 2003). However, estimates vary widely, often due to differences in scope, assumptions, and methods (Richards and Stokes, 2004a, 2004b; Honkomp and Schier, 2023). This variation highlights the need for modeling frameworks that explicitly trace how harvest, product flows, and market dynamics interact to shape carbon outcomes, rather than treating sequestration in forests or HWPs as exogenous inputs.

Traditional forest sector models such as FASOM (Adams et al., 1996), GTM (Sohngen et al., 1999), and NFSM (Jåstad, 2020; Mustapha, 2016) have been widely used to analyze mitigation strategies including carbon pricing, afforestation, and biomass supply. However, they are typically anchored in a single-objective paradigm, maximizing welfare under external constraints rather than directly comparing alternative carbon allocation strategies (Favero et al., 2020; Fuller et al., 2025; Latta et al., 2013; Sohngen and Mendelsohn, 2003). This creates a gap: near-optimal adjustments in harvest, production, and trade that could deliver similar welfare but very different carbon outcomes remain unexplored. Modeling-to-Generate-Alternatives (MGA) addresses this gap by systematically exploring near-optimal solutions within a defined welfare slack (Brill et al., 1982; Price and Keppo, 2017). Unlike exogenous scenario analysis, MGA endogenously identifies alternative solutions, revealing hidden trade-offs across strategies. MGA has been applied in land-use planning, water management, and energy systems (Brill et al., 1982; Chen et al., 2022; Mendoza, 1987; Price and Keppo, 2017; Yeomans, 2019; Zhang et al., 2023; Chang et al., 1982), but not in forest carbon mitigation. Its application here represents both a methodological innovation and a disciplinary contribution: shifting forest economics beyond single-optimum analysis and enabling a structured assessment of carbon cost trade-offs between forests and HWPs.

This study applies MGA within the Nordic Forest Sector Model (NFSM) to evaluate two contrasting carbon objectives: (1) maximizing carbon storage in harvested wood products (Max.HWPCarbon), and (2) maximizing total carbon retention by combining avoided harvest with HWP storage (Max.GrossCarbon). For each objective, we generate near-optimal strategies under varying welfare slacks and derive marginal abatement cost curves. This allows us to situate the results within broader carbon pricing benchmarks and provide a disciplined comparison of cost-effectiveness, industrial shifts, and trade-offs between bioeconomy expansion and forest conservation. The paper makes three contributions. First, it introduces MGA into forest sector modeling, extending methodological practice beyond the single-optimum paradigm. Second, it provides the first systematic comparison of cost curves for HWP versus forest retention strategies in the Nordic context. Third, it reframes forest carbon mitigation as a value-chain problem, linking sequestration outcomes to industrial production and trade. Together, these contributions place the study within the broader literature on marginal abatement costs, forest economics, and climate policy design.

The remainder of the paper is organized as follows: Section 2 outlines the methodology developed in this study, which includes the introduction of the model NFSM, the application of MGA into NFSM, method of cost estimation, sensitivity analysis and assumptions and data. This is followed by the presentation of the results (Section 3) and discussion (Section 4) highlighting the implications of the analysis. Section 5 provides the main conclusions of the study.

2. Methodology

2.1. Model framework

A spatial partial equilibrium forest sector model, the Nordic Forest Sector Model (NFSM), is used in this study. It builds on the structure of the Norwegian Trade Model (NTM) (Bolkesjø et al., 2005, 2006; Trømborg and Solberg, 1995; Trømborg and Sjølie, 2011) and follows the same core principles as the Global Trade Model (GTM) (Kallio et al., 1987). NFSM has been applied in several recent studies to assess strategic developments in the Nordic forest sector, including the feasibility and impacts of biofuel deployment in the Nordic region (Jåstad et al., 2019, 2020, 2021, 2023; W. F. Mustapha et al., 2017, 2019), impact of Bio-CCS on biomass competition (Hu et al., 2023) and policy induced market leakage (Hu et al., 2024).

2.1.1. Model structure

NFSM consists of four core components:

- Timber supply – represented by supply elasticities and changes in growing stock.
- Industrial production – determined by input–output coefficients specifying raw material requirements and costs per unit of output.
- Consumer demand – modeled with regional demand profiles, GDP-dependent demand elasticities, and product prices.
- Trade – flows are governed by spatial price equilibrium, where interregional trade occurs until price differences equal transport costs.

The main product set includes six roundwood assortments (spruce, pine, and non-coniferous sawlogs and pulpwood), nine intermediate products (including pulp and industrial residues), and thirteen final products (sawnwood, board, paper grades, firewood, and energy use).

The key endogenous decision variables in NFSM are (i) harvest volumes of roundwood assortments and (ii) production levels of harvested wood products (HWPs) such as sawnwood, panels, and paper. These outputs form the basis for the carbon accounting applied in this study.

2.1.2. Spatial coverage

The model covers Norway, Sweden, Finland, and Denmark (Fig. 1). Norway, Sweden, and Finland are each subdivided into ten regions, while Denmark is represented as one region due to its smaller forest sector. The rest of the world (ROW) is represented as a single aggregate trading partner, allowing imports and exports of raw materials, intermediate products, and HWPs.

2.1.3. Equilibrium mechanism

Equilibrium is achieved by maximizing total welfare, defined as the sum of producer and consumer surplus net of harvest, production, transport, labor, and investment costs. At the equilibrium point, roundwood supply, industrial production, and trade are determined endogenously. Industrial production continues until marginal costs equal product prices, while trade balances until price gaps equal transport costs. Roundwood and residue prices reflect marginal supply costs, while final product prices reflect marginal industrial costs under equilibrium. The optimization problem can be solved at the smallest time resolution allowed in the model, i.e., one year. In this study, the NFSM is run at one base year, i.e., the year 2018. For more model assumptions and the dataset, please refer to the Appendix of (Jåstad, 2020).

2.2. Modeling-to-generate-alternatives (MGA) framework

2.2.1. Anchor solution and slack values specification

The analysis begins with an anchor solution, obtained by solving NFSM under its original welfare-maximizing objective. This anchor de-

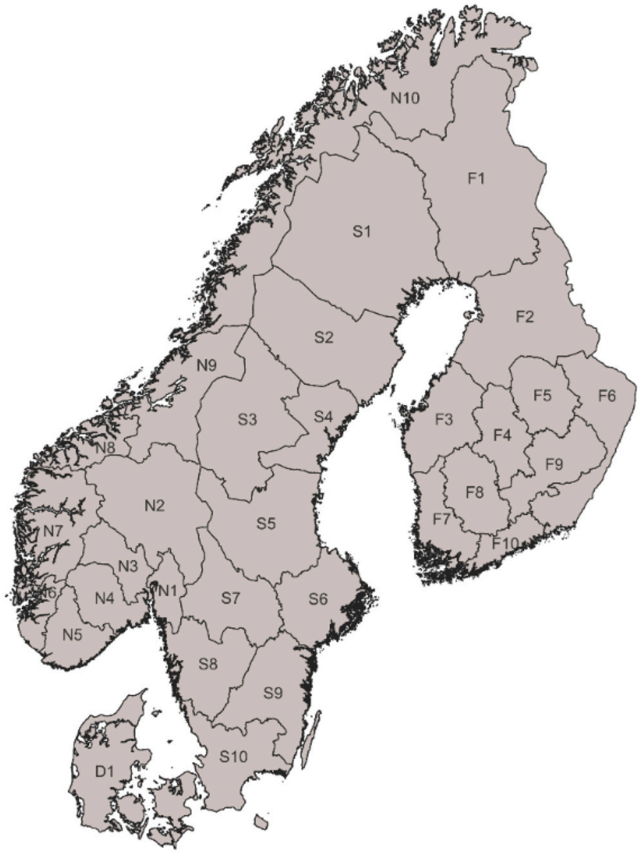

Fig. 1. The spatial resolution of Nordic Forest Sector Model (NFSM), covering Norway, Sweden, and Finland in 10 regions each and 1 region in Denmark.

fines the benchmark outcome for total welfare (S_{anchor}) as well as harvest, production, trade, and carbon levels in the base year. All alternative carbon-focused strategies are evaluated relative to this reference point.

To explore near-optimal strategies, the Modeling-to-Generate-Alternatives (MGA) framework is applied (Price and Keppo, 2017). MGA relaxes the strict optimality requirement by introducing a user-defined slack, typically expressed as a small percentage deviation from the anchor welfare (Chang et al., 1982). The constrained welfare level for a given slack value is:

$$S_i = (1 - slack_i) \bullet S_{anchor}$$

where $slack_i$ is the tolerance level applied. In this study, the slack values varied between 0.1 % and 10 % of anchor welfare. Instead of a uniform step size, we applied an adaptive grid that provides finer resolution at low welfare losses, where marginal abatement costs are most sensitive, and coarser intervals at higher slack levels. This approach balances numerical tractability with policy relevance, ensuring detailed representation of the low-slack region while avoiding excessive computation in ranges where welfare losses become less credible. If a run became infeasible before 10 %, the analysis was limited to the last feasible slack level.

2.2.2. Carbon optimization objectives

Two alternative carbon objectives are introduced to capture contrasting forest-based mitigation strategies. The rationale for defining both objectives is that forests and harvested wood products (HWPs) represent distinct but complementary carbon pools, and the trade-offs between them are central to climate policy and forest economics. Because the forest stock is far larger than the HWP pool, optimizing absolute levels would trivially favor forest retention. Instead, both objectives are formulated in incremental terms relative to the welfare-maximizing anchor, so that only carbon changes attributable to the modeled strategy are credited.

- Max.HWPCarbon (bioeconomy-oriented strategy): rewards additional carbon stored in long-lived wood products weighted by product half-lives.
- Max.GrossCarbon (conservation-oriented strategy): combines these HWP gains with additional standing forest stock preserved through reduced harvest.

This design ensures comparability across strategies and reveals the trade-off between continued industrial use and forest retention under a common welfare slack. The mathematical expressions are detailed below.

2.2.3. Max.HWPCarbon

For each HWP product *hwp*, NFSM outputs the endogenous annual production level φ_{hwp}, which is treated as the inflow into the HWP carbon pool. HWP stocks are calculated using first-order decay with product-specific half-lives HL_{hwp}:

$$L_{hwp} = \frac{\ln 2}{HL_{hwp}}$$

The steady-state stock supported by production φ_{hwp} (is)

$$Q^{obj1}_{hwp} = \frac{\varphi_{hwp}}{L_{hwp}} * k^c_{hwp}$$

Where k^c_{hwp} is the carbon content factor (tC per t of product, later converted to tCO_2). *hwp* and *obj* denote HWP categories and objective functions, respectively.

The incremental HWP carbon stock relative to the anchor(is)

$$\Delta Q^{obj1}_{hwp} = \frac{\Delta\varphi_{hwp}}{L_{hwp}} * k^c_{hwp} = \frac{\varphi^i_{hwp} - \varphi^{anchor}_{hwp}}{L_{hwp}} * k^c_{hwp}$$

The objective of Max.HWPCarbon (bioeconomy-oriented strategy) maximizes the steady-state carbon stock supported by HWP inflows.:

$$Max. \sum_{hwp} \Delta Q^{obj1}_{hwp}$$

2.2.4. Max.GrossCarbon

The Max.GrossCarbon objective extends the HWP-only formulation by explicitly adding the carbon preserved in forests through avoided harvest. In a static one-year setting, forest growth is constant across anchor and MGA scenarios, so the relevant variation in forest carbon arises from differences in harvest relative to the anchor. The Δ term in Max.GrossCarbon represents two components: (i) additional carbon stored in HWPs compared to the anchor, and (ii) additional standing stock retained due to reduced harvest:

$$\Delta Q^{obj2}_{hwp+w} = \frac{\Delta\varphi_{hwp}}{L_{hwp}} * k^c_{hwp} + \Delta H_w * k^c_w$$

$$= \frac{\varphi^i_{hwp} - \varphi^{anchor}_{hwp}}{L_{hwp}} * k^c_{hwp} + \left(H^i_w - H^{anchor}_w\right) * k^c_w$$

where $H^i_w - H^{anchor}_w$ is the avoided harvest of roundwood in the forest (in cubic meters), and k^c_w is carbon content factor convert it to tCO_2. *w* denotes the roundwood categories, *i* denotes the slack values. Here, the two carbon pools are not independent: roundwood harvested for HWP production cannot simultaneously contribute to standing forest carbon. Thus, forest conservation and HWP expansion directly compete for the same resource base, explicitly requiring the model to balance this trade-off between conservation and production. Objective function of Max.

GrossCarbon (conservation-oriented strategy) writes as:

$$\text{Max.}\left[\sum_{hwp+w}\Delta Q^{obj2}_{hwp+w}\right]$$

2.2.5. MGA procedures

The optimization process for each slack value and carbon objective is as follows:

1. Anchor solution: Solve NFSM with welfare maximization to determine the anchor economic welfare S_{anchor}, and anchor carbon storage in targeted carbon pools.
2. $slack_i$ constraint: Add $S_i = (1 - slack_i)^* S_{anchor}$ as a new constraint in the model.
3. Carbon objective: *Re*-run the model with new objective functions to get new carbon storage in the targeted carbon pools for the two objective functions, respectively.
4. Iteration: Repeat steps 2 and 3 for each slack value under each objective function.

2.3. Cost estimation

For each slack level $slack_i$, the incremental carbon gain is estimated as:

$$\Delta Q^{obj1}_i = Q_i - Q_{anchor} = \left(\varphi^i_{hwp} - \varphi^{anchor}_{hwp}\right)\Big/ L_{hwp} {}^* k^c_{hwp}$$

$$\Delta Q^{obj2}_i = Q_i - Q_{anchor} = \left(\varphi^i_{hwp} - \varphi^{anchor}_{hwp}\right)\Big/ L_{hwp} {}^* k^c_{hwp} + \left(H^i_w - H^{anchor}_w\right) {}^* k^c_w$$

The corresponding welfare loss is:

$$\Delta S^{obj}_i = S^{obj}_i - S_{anchor}$$

Average abatement cost (AC) is:

$$AC^{obj}_i = \frac{\Delta S^{obj}_i}{\Delta Q^{obj}_i}$$

Exponential functions are fitted to the welfare (ΔS^{obj}_i)–carbon $\left(\Delta Q^{obj}_i\right)$ relationship:

$$\Delta S^{obj}_i \sim a \bullet \left(\Delta Q^{obj}_i\right)^b$$

and analytically differentiated marginal abatement costs (MACs) is:

$$MAC\left(\Delta Q^{obj}_i\right) = a \bullet b \bullet \left(\Delta Q^{obj}_i\right)^{b-1}$$

2.4. Sensitivity analysis

To assess the robustness of the results, a set of sensitivity experiments was carried out on four key parameters that influence carbon accounting and market outcomes: (i) carbon content of biomass, (ii) transport costs, and (iii) the half-life of harvested wood products. Each sensitivity case was run with a re-computed anchor solution before applying MGA.

- Carbon content. The conversion from biomass to carbon depends on assumptions about wood density, moisture content, and carbon fraction. To test the influence of these assumptions, the carbon content factor varied by ±20 % across all wood product categories.
- Transport costs. NFSM represents trade through a spatial price equilibrium in which flows occur when interregional price differences equal transport costs. To capture the effect of market integration, transport costs were uniformly scaled by ±20 % relative to the baseline. The reduction reflects efficiency gains or lower fuel costs, while the increase mimics frictions such as carbon pricing on freight, congestion, or import restrictions. These adjustments test how sensitive the carbon–cost trade-offs are to assumptions about tradability.
- Half-life of wood products. The residence time of carbon in HWPs depends on the assumed half-lives of different product categories. To test the robustness of results to this assumption, half-lives were uniformly varied by ±25 % across products. This adjustment captures uncertainties in product use, recycling, and disposal patterns, which directly influence the effective carbon retention in HWPs.
- Locking constraints. In addition to these parametric tests, two structural constraints were evaluated: (i) locking net trade flows of biomass at their baseline levels (LockTrade), and (ii) locking total roundwood harvest at its baseline level (LockHarvest). These scenarios directly restrict the main adjustment channels in the model and therefore test the sensitivity of results to rigid market or harvest policies.

2.5. Assumptions and data

The analysis is conducted for a single representative year, 2018, which provides the calibration point for harvest, production, and trade levels in the Nordic forest sector. This static setup isolates immediate allocation trade-offs between forest and harvested wood product (HWP) carbon pools under alternative objectives, while abstracting from intertemporal forest dynamics and long-run technological change.

Carbon accounting. Conversion of wood and wood products into carbon storage is based on product-specific density, carbon content, and moisture content values (Table 1). All carbon values are reported in CO_2 equivalents, using a molecular weight ratio of 44.01/12.01. Half-lives for harvested wood products (HWPs) are drawn from IPCC guidelines (IPCC, 2006; 2014) and recent literature, with long-lived categories such as sawnwood and panels assigned multi-decade residence times, and short-lived paper products assigned shorter lifespans, as shown in Table 2.

Economic assumptions. Non-forest sector prices (e.g., labor, energy, capital) are treated as exogenous and static. Transport costs are specified

Table 1
Biophysical parameters for carbon accounting, including density, moisture content, and carbon content for each HWP in NFSM. (Note that when the units of the model data are already expressed in kg/m^3, the density factor is effectively normalized to 1.)

Category	Products	density	carbon content%	moisture content%
Harvest	Spruce Sawlogs	450	48 %	40 %
	Pine Sawlogs	450	48 %	40 %
	Spruce Pulpwood	352	48 %	40 %
	Pine Pulpwood	352	48 %	40 %
	Non-Coniferous Sawlogs	505	48 %	40 %
	Non-Coniferous Pulpwood	444	48 %	40 %
	Harvesting residues	352	48 %	40 %
HWP	Spruce Sawnwood	450	48 %	40 %
	Pine Sawnwood	450	48 %	40 %
	Non-Coniferous Sawnwood	505	48 %	40 %
	Cross-laminated timber	450	48 %	40 %
	Particle board	306	48 %	40 %
	Plywood	675	48 %	40 %
	Fiberboard	1	48 %	40 %
	Printing and writing paper	1	44 %	0 %
	Newsprint	1	48 %	0 %
	Linerboard	1	48 %	0 %
	Other paper and paperboard	1	48 %	0 %

Table 2
Standard half-life values used in the main analysis and alternative values applied in the sensitivity tests.

	Standard half-life (yr)	+25 % half-life (yr)
Sawnwood	35	44
Board	25	31
Paper	2	1.5

by product–route combinations and govern interregional trade flows through the spatial price equilibrium mechanism. Baseline transport cost values (prior to the ±20 % variations applied in the sensitivity analysis) are documented in the Appendix of Jåstad (2020). These values provide the reference point for our simulations, and their robustness is subsequently tested through sensitivity analysis.

Scope and exclusions. The analysis is restricted to a static, short-term horizon (e.g., year 2018). Substitution effects of HWPs, i.e., avoided emissions from replacing carbon-intensive materials or energy carriers, are excluded. These effects depend on end-use, lifetime, and consumer-side system boundaries, which lie outside the scope of a sectoral production model. As a result, reported outcomes reflect direct carbon storage in forests and HWPs rather than broader lifecycle effects.

3. Results

3.1. Cost of maximizing CO_2 storage in NFSM

Fig. 2 presents the total, marginal, and average abatement costs plotted against the corresponding CO_2 gains for optimizing carbon stored in harvested wood products (HWP) only (Max.HWPCarbon), and for optimizing the net CO_2 gain from both uncut forest stock and HWP pools together (Max.GrossCarbon).

The results clearly show that, for a given level of compensated welfare loss (slack), the Max.GrossCarbon objective achieves greater carbon sequestration in its targeted pool than the Max.HWPCarbon objective. Marginal costs, derived from the fitted total cost curves, reveal a wide disparity between the two strategies. For Max.HWPCarbon, marginal abatement costs rise steeply, ranging from about €40 to €1200 per tCO_2. In contrast, Max.GrossCarbon achieves carbon gains at significantly lower marginal costs, roughly €15 to €460 per tCO_2, highlighting the relative efficiency of reducing harvest and allowing forest retention. Average abatement costs show a similar pattern. For Max.GrossCarbon, they range from about €8 to €260 per tCO_2, while for Max.HWPCarbon they span approximately €20 to €680 per tCO_2.

The underlying economic mechanism explains these divergent cost trajectories. Forest carbon accumulates at relatively low cost when harvest levels are reduced, as stock accumulation provides immediate, low-cost sequestration gains. In contrast, HWP storage is constrained by limited product lifespans and industrial production capacities. As slack increases, additional carbon storage must be forced into increasingly

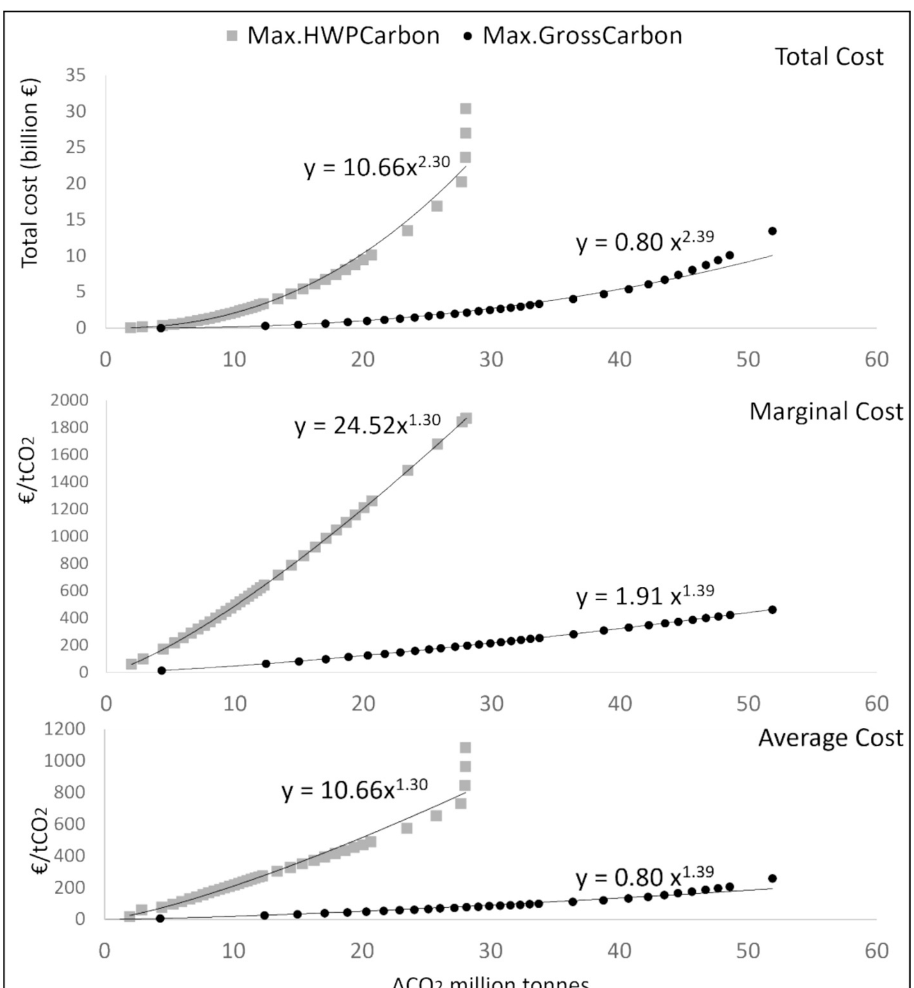

Fig. 2. The total cost, average cost, and marginal cost of maximizing CO_2 sequestration in the target carbon pool of Max.HWPCarbon and Max.GrossCarbon.

shorter-lived or less efficient products, producing diminishing returns and a steep rise in marginal costs. This trade-off underscores the structural differences between conserving standing forest carbon and relying on product-based sequestration.

These findings carry important policy implications. Policies that rely exclusively on boosting HWP stocks may lead to rapidly escalating costs and declining efficiency, while forest conservation strategies, though more cost-effective, imply substantial contractions in timber supply and associated industrial output. The results therefore highlight the need to design integrated carbon management strategies that balance forest retention with sustainable wood product use, and that anticipate trade and leakage effects across the value chain.

Despite these differences, the similarity in cost elasticity between the two objectives suggests that both strategies exhibit comparable sensitivity to changes in compensation levels. However, the substantially lower absolute costs of maximizing the carbon storage through avoided harvest combined with HWPs (Max.GrossCarbon) strategy make it more attractive for policymakers aiming to maximize sequestration within constrained budgets. Overall, these results underscore the importance of integrated carbon management strategies that balance economic viability with climate objectives in forest policy design.

It is important to note that the modeled carbon responses are driven solely by adjustments in roundwood harvest and HWP production levels, as other factors, such as forest rotation management, afforestation, or the substitution effects of HWPs, are not endogenously represented in the model. While this provides a focused lens on internal sectoral trade-offs, future work could extend the analysis to incorporate broader land-use interactions and temporal carbon dynamics for a more comprehensive assessment.

3.2. Industrial and market implications

This section presents the effects of the two carbon optimization objectives, Max.HWPCarbon and Max.GrossCarbon, on roundwood harvest, industrial production, trade flows, and carbon storage in the Nordic forest sector. Fig. 3 illustrates percentage changes in production and net exports relative to their baseline ('anchor') values under four slack levels: 1 %, 2 %, 3 %, and 4 %. Positive changes in % in net exports (bars above the x-axis) indicate increased net exports, while negative values (below the x-axis) reflect increased net imports. In cases where the percentage change exceeds 100 %, the model indicates a transition from a net exporter to a net importer. The results reflect how climate-oriented strategies reshape the internal dynamics of the sector through adjustments in wood supply and product output, with important implications for both industrial and market dynamics.

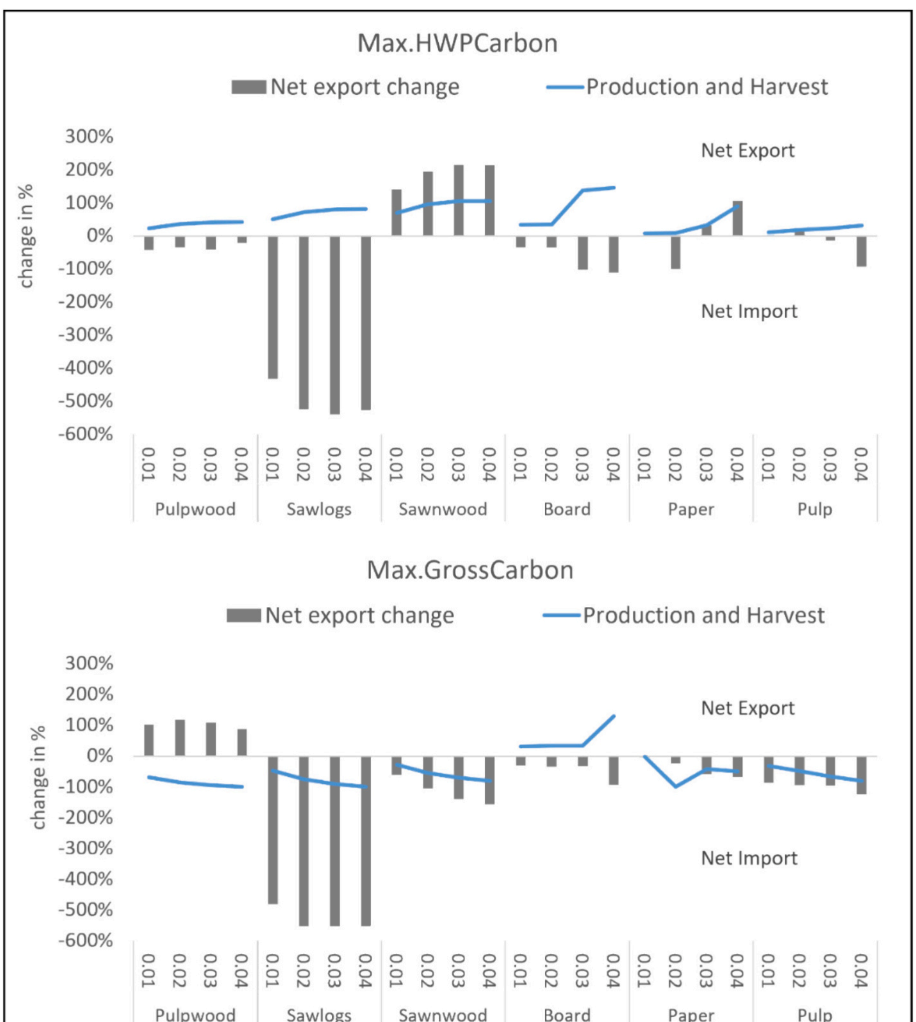

Fig. 3. The changes in production and net export of roundwood and HWP for the slack values 1 %, 2 %, 3 % and 4 %. The results for the goal of Max.HWPCarbon and Max.GrossCarbon are shown in the upper and lower part of the figure, respectively.

3.2.1. Max.HWPCarbon: expanding production and trade at the expense of forest carbon

The Max.HWPCarbon objective prioritizes carbon storage in harvested wood products (HWPs), encouraging increased use of long-lived products such as sawnwood. To meet this objective, the model increases domestic roundwood harvest, particularly of industrial sawlogs, which rise by 40 % to 80 % across slack values. Pulpwood harvest also increases, but more modestly (20 % to 40 %), due to its shorter lifespan and lower contribution to carbon storage. This expanded harvest feeds a significant increase in industrial production, especially for sawnwood, which doubles or triples relative to the anchor level. Sawnwood serves as a key lever for building the HWP carbon pool due to its long carbon residence time. Panel and pulp production also increases, although to a lesser extent. To support this production surge, the model increasingly relies on sawlog imports, which grow by several hundred percent, up to 500–600 %, as the domestic supply becomes insufficient. Net exports of sawnwood also rise sharply, reflecting a shift toward export-oriented growth in the bioeconomy. However, this increase in imports raises concerns about carbon leakage, as domestic gains in HWP carbon may be offset by increased harvest pressure in exporting countries.

3.2.2. Max.GrossCarbon: forest conservation with industrial contraction and trade shifts

The Max.GrossCarbon objective maximizes total carbon storage in forests and HWPs, accounting for carbon losses from the harvesting of roundwood. To achieve this, the model progressively reduces roundwood harvest, with both sawlogs and pulpwood declining. Sawlog harvests fall more rapidly, given their higher carbon content and larger role in industrial emissions. By the time slack reaches 4 %, domestic harvesting halts entirely. This sharp decline in harvest leads to a contraction in industrial production. Sawnwood output falls steeply and approaches zero at high slack levels, with similar trends in pulp and panel production. The contraction reflects the model's strong incentive to preserve standing forest carbon stocks rather than sustain material output. Trade patterns adjust in response. Net exports of HWPs, particularly sawnwood, decline as production shrinks.

3.3. Implications

These findings illustrate how different climate objectives translate into fundamentally different industrial and trade structures. The strategy of maximizing stored carbon in HWP supports an expansion of the forest economy, increasing domestic processing and exports while risking higher marginal costs and forest carbon losses. By contrast, the strategy of maximizing stored carbon in forests and HWP prioritizes forest conservation, drastically reducing the domestic wood supply and potentially creating risks of market leakage through increased raw material imports. These outcomes underscore the importance of aligning forest mitigation goals with industrial and trade policies to avoid unintended displacement effects and ensure long-term sustainability. More broadly, they demonstrate that carbon allocation strategies cannot be assessed in isolation from the forest value chain, since choices about sequestration directly reshape production structures, trade patterns, and sectoral competitiveness. In this sense, the results confirm the study's contribution of reframing forest-based mitigation as a value-chain problem, linking climate objectives with industrial and market dynamics.

3.4. Sensitivity analysis results

Fig. 4 and Fig. 5 compare total abatement costs across the base case and sensitivity runs. The results show that imposing constraints on either trade or harvest substantially increases the total cost of carbon storage, with the harvest cap producing the strongest effect. Among the tested model parameters, carbon content shows the most visible impact on estimated costs, with higher carbon content lowering estimated costs as expected.

The cost impact of harvest caps is particularly significant under the

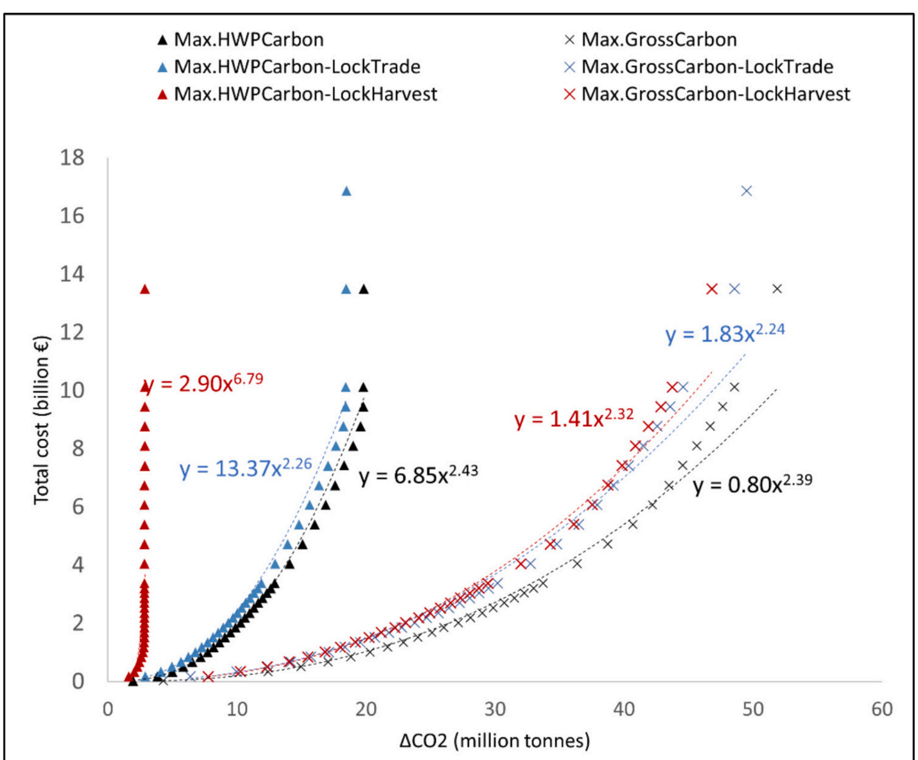

Fig. 4. Total abatement costs in the baseline and structural sensitivity scenarios. Results are shown for the base case, a locked trade scenario (LockTrade), and a locked harvest scenario (LockHarvest).

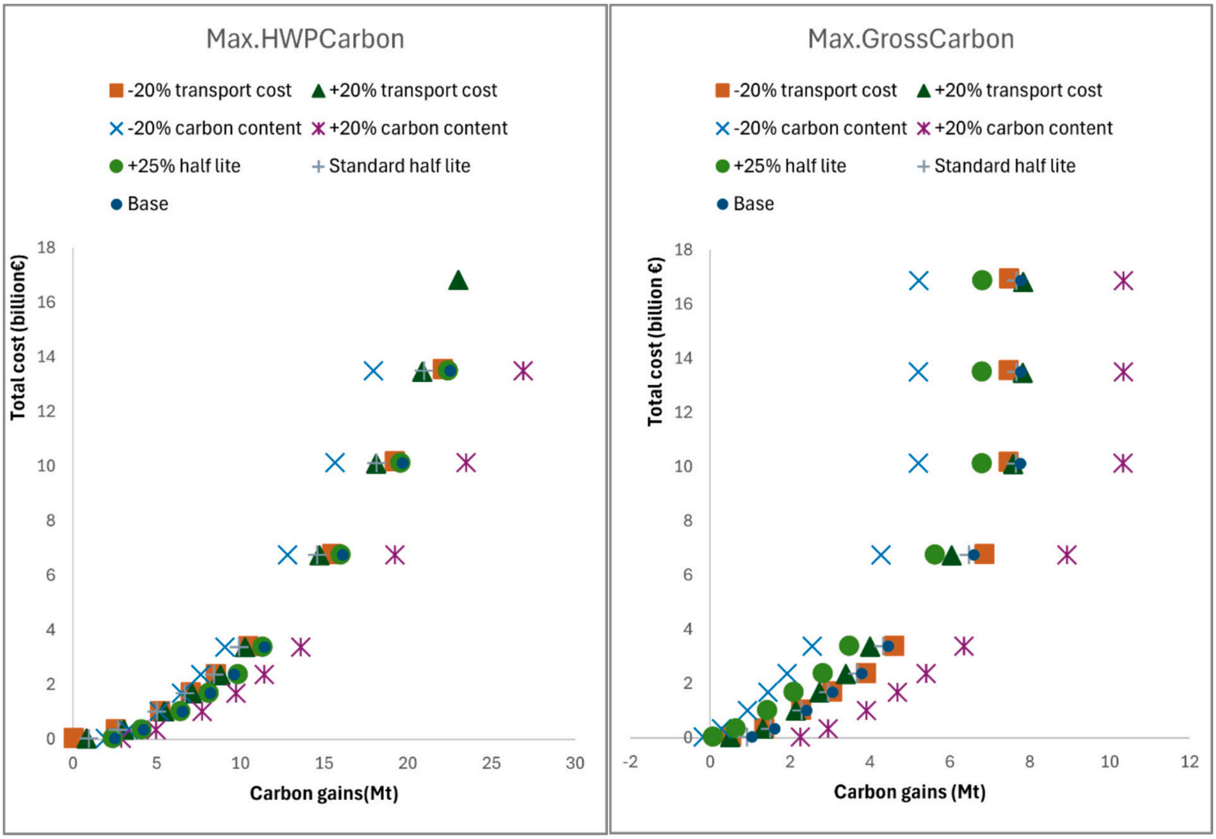

Fig. 5. Total abatement costs in the baseline and parametric sensitivity scenarios. Results are shown for the base case (black) alongside variations in carbon content (±20 %), transport costs (−20 %, +20 %), and half-life of harvested wood products (±25 %).

Max.HWPCarbon objective. When domestic harvests are restricted, the model loses its main lever for expanding long-lived wood product output, forcing reliance on imports or lower-productivity processes and leading to sharply rising abatement costs. The Max.GrossCarbon objective shows much lower sensitivity to such constraints, since reduced harvesting is already part of its optimal strategy.

4. Discussion

4.1. Comparing modeled abatement costs with literature benchmarks

The marginal abatement costs (MACs) estimated in this study fall within the broad range reported in the forest economics and climate mitigation literature, but also highlight important distinctions between carbon storage strategies. In particular, the results underscore the cost-efficiency of forest-based carbon retention compared to harvested wood product (HWP) sequestration under current model assumptions.

The marginal costs of storing carbon by maximizing net forest stock and wood products (Max.GrossCarbon) range from roughly €15 to €460 per tCO_2, whereas strategies focused solely on increasing carbon in harvested wood products (Max.HWPCarbon) are significantly more expensive, with marginal costs rising from about €40 up to €1200 per tCO_2. These findings are broadly consistent with other forest-sector modeling studies. For example, Honkomp and Schier (2023) review average annual carbon prices in forest-sector models and find a very wide span—from about \$1 to nearly \$6000 per tCO_2—though most fall below \$100. Similarly, Richards and Stokes (2004a, 2004b) report marginal costs between \$0 and \$50 per tCO_2 depending on region and methodology. Sohngen and Mendelsohn (2003) estimate long-run marginal prices of \$60–190 per tCO_2 in dynamic models, while Sedjo et al. (2001) derive comparable values from global supply curves. Our modeled costs for Max.GrossCarbon align with the lower to mid-range of these estimates, while those for Max.HWPCarbon fall toward the upper end, particularly at higher slack levels where diminishing returns dominate. Other empirical studies reinforce this contrast. Liu et al. (2022) report afforestation costs in Taiwan of about \$35–65 per tCO_2, within the range of our Max.GrossCarbon estimates and lower than many energy-sector mitigation options. Similarly, Deng et al. (2022) show that forest management strategies are more responsive to carbon prices than to timber prices, highlighting the potential for low-cost mitigation via harvest reductions—a dynamic reflected in the relatively flat cost trajectory of Max.GrossCarbon in our study.

Benchmark values from markets and regulatory frameworks provide further comparison. The EU ETS, for instance, reported an average allowance price of about €65 per tCO_2 in 2024 (Trading Economics, 2024). The lower range of our modeled Max.GrossCarbon costs falls below this benchmark, suggesting conservation-based strategies could be cost-competitive if bio-carbon is credited on par with fossil carbon. By contrast, much of the Max.HWPCarbon curve lies above this benchmark, suggesting limited feasibility without subsidies or structural changes in HWP markets. The social cost of carbon (SCC) has a mean value near \$55 per tCO_2, though estimates range from negative values to over \$2000 depending on assumptions (Wang et al., 2019). Again, Max.GrossCarbon compares favorably to this reference, while Max.HWPCarbon would exceed the SCC under most cases. Finally, opportunity cost-based estimates, such as REDD+ case studies (Ndjondo et al., 2014; Bousfield et al., 2022), place compensation needs for logging reductions at about \$5–25 per tCO_2. Our lower-bound Max.GrossCarbon estimate is close to this range, showing consistency with known benchmarks for forest protection payments in tropical contexts.

The comparison suggests that the Max.GrossCarbon strategy, which relies on reduced harvesting and forest carbon accumulation, can achieve substantial CO_2 gains at costs that are competitive with other mitigation sectors and policy benchmarks. By contrast, the Max.

HWPCarbon strategy, while aligned with bioeconomy expansion goals, exhibits rapidly increasing marginal costs and limited cost-effectiveness at higher levels of sequestration. These findings underscore the importance of prioritizing cost-effective mitigation strategies and suggest that approaches centered on forest conservation and material efficiency may deliver greater climate benefits per euro invested, offering a more efficient use of resources in forest-based carbon policy. They also highlight the utility of MACs as a decision-support tool when comparing forest-sector mitigation options to broader energy and land-use strategies, while the scope of these studies, encompassing methodologies, models employed, geographic focus, mitigation options considered, and cost types, may complicate the comparison.

Together, the cost results suggest that forest-based strategies can provide carbon benefits more cost-effectively. However, such strategies pose challenges for the economic performance of the Nordic forest industries. To address this, future bioeconomy policies should emphasize innovation and value creation, recognizing that the interdependence between climate change mitigation and other value-added actions, such as ecosystem service-based economic opportunities (e.g., eco-tourism) is important (Luhas et al., 2021). Adopting an integrated, landscape-level perspective is essential for balancing environmental objectives with economic resilience.

4.2. Balancing forest carbon storage and wood use in climate mitigation

The results of this study illustrate the trade-offs involved in allocating forest resources between carbon sequestration in standing biomass and carbon storage or substitution benefits through harvested wood products. While the modeled outcomes suggest that, under certain assumptions, wood use is a more costly mitigation option than forest carbon storage, recent empirical findings by Soimakallio et al. (2021) further emphasize the risks of intensified harvesting. Their study finds that in Finland, higher harvest levels almost certainly increased net GHG emissions, largely due to diminished forest carbon sinks and elevated biogenic emissions, which were not fully compensated by fossil fuel substitution. Reversing such outcomes would require a greater share of long-lived wood products, implementation of bioenergy with carbon capture and storage (BECCS), and a minimization of forest carbon losses. These results highlight the importance of full-system carbon accounting and suggest that forest-based mitigation strategies should prioritize preserving carbon stocks unless enabling conditions for net climate benefits from wood use are clearly met.

As the green transition accelerates and the global economy expands, the demand for wood-based products is expected to grow significantly (Held et al., 2022). This trend makes increased forest harvesting, both domestically and internationally, likely unavoidable. However, this study highlights the high marginal cost associated with strategies that focus solely on increasing carbon storage in harvested wood products (HWP). Under such approaches, intensive harvesting may lead to diminishing carbon returns, higher economic costs, and negative environmental side effects. In this context, sustainable harvesting practices, such as selective logging instead of clear-cutting, warrant greater attention. These methods have been shown to support soil recovery, reduce carbon emissions, and preserve biodiversity (Ahtikoski et al., 2022; Ding et al., 2017; Reader, 1987; Wu et al., 2011). Moreover, enhancing the material efficiency of forest resource use should be prioritized. Strategies such as cascading use, where wood is used sequentially for different purposes before energy recovery, and recycling, can significantly increase the carbon and economic value derived from each unit of harvested wood (Jarre et al., 2019; Tanguay et al., 2021).

4.3. Limitations and further research needs

This study provides an exploratory assessment of carbon sequestration trade-offs in the Nordic forest sector using a partial equilibrium forest sector model coupled with Modeling to Generate Alternatives (MGA). While the results yield important insights into mitigation cost structures and industrial impacts, several limitations should be acknowledged.

The carbon response is modeled for a single year without intertemporal dynamics, and the substitution effect of harvested wood products (HWPs) is not included. Research shows that the timeframe is critical when comparing the climate benefit of forest sinks versus HWP-related substitution (Schulte et al., 2022). In the short to medium term, conserving forest carbon typically provides greater mitigation, even under high substitution assumptions. Over longer horizons (30–100+ years), however, cumulative substitution benefits may outweigh forest carbon losses, provided substitution factors remain constant. Yet this assumption is increasingly questioned. Brunet-Navarro et al. (2021) projected that substitution benefits could decline by 33 % by 2030 and up to 96 % by 2100, in line with global decarbonization trajectories. As renewable energy and low-carbon construction alternatives expand, the marginal displacement value of wood products may diminish substantially. By not accounting for intertemporal forest dynamics, product decay, and time-varying substitution effects, this study cannot fully capture evolving trade-offs between conservation and material use. Future research should therefore extend the framework to a dynamic, multi-period model that tracks forest growth, product decay, and substitution benefits over time, with substitution factors allowed to change alongside technological progress and decarbonization pathways. This corrective step would address the static bias and enable more realistic, policy-relevant assessments of long-term trade-offs.

This study applies an established modeling technique (MGA) in a new context to explore carbon sequestration costs across forest and product pools. While the approach is technique-driven, the aim has been to highlight practical implications for incentive design in the Nordic forest sector. The study does not invent a new method but contributes by linking an existing approach to policy-relevant questions. The future research could embed such modeling approaches more explicitly in problem-driven policy settings, for example by tailoring the objective function or scenario design to directly support ongoing national carbon accounting debates, EU-level reporting mandates, or incentive program design. Additionally, the MGA method, while effective for exploring the near-optimal solution space, does not provide probabilistic uncertainty estimates or account for endogenous technological change. The choice of slack values, while methodologically justified, remains arbitrary to some extent and should be interpreted as a tool for exploring trade-off boundaries, rather than suggesting policy prescriptions. Complementary methods such as stochastic optimization or probabilistic uncertainty analysis could be integrated to address uncertainty and technological change more comprehensively.

The forest sector model assumes perfect foresight and equilibrium, abstracting from shocks and behavioral responses. Future extensions could incorporate bounded rationality, policy shocks, or disequilibrium dynamics, either through coupling with dynamic stochastic models or through scenario analysis that relaxes the equilibrium assumption. Similarly, the treatment of imports could be improved by explicitly modeling substitutability between domestic and imported biomass, thereby reducing the risk of overstated trade responses.

Lastly, extreme results under the maximizing the gross carbon storage (Max.GrossCarbon) strategy, such as a five- to six-fold increase in roundwood imports and near-zero domestic harvest at high slack values, are unrealistic. Nevertheless, they serve to illustrate the model's internal logic under purely carbon-driven optimization, operating within the structural constraints and assumptions of the framework. The main reason for these outcomes is that the model does not incorporate sustainability boundaries, such as limits on harvest increases or import volumes, which would normally be applied to ensure ecological or operational credibility. However, this omission is intentional, as the aim of the study is not to simulate feasible policy scenarios, but to theoretically explore the trade-offs of aggressive carbon prioritization under existing system boundaries. This approach limits the realism of the sequestration pathway and reinforces that the results should be interpreted as upper-bound cost indicators rather than direct policy prescriptions. The extreme trade shifts and harvest collapses highlight potential points of friction between ambitious climate objectives and current market structures, rather than suggesting such outcomes are likely or desirable. Likewise, the finding that no feasible solution is identified beyond a 4 % reduction in total under the Max.GrossCarbon strategy reveals that extreme carbon prioritization becomes structurally incompatible with economic viability beyond a certain threshold, a critical insight of the analysis. To address this, future research should integrate ecological and operational sustainability boundaries (e.g., harvest limits, import capacity constraints) into the optimization framework. This corrective step would avoid implausible outcomes while preserving the value of MGA for exploring near-optimal trade-offs.

In sum, while the model provides useful stylized insights, the results should be interpreted as indicative of structural trade-offs under simplified assumptions, not as forecasts or precise policy guidance. To strengthen the contribution, future research should (i) extend to multi-period dynamic models, (ii) broaden sensitivity analyses, (iii) embed substitution effects, and (iv) incorporate ecological and operational constraints. These corrective measures would allow the framework to evolve from a theoretical exploration into a more comprehensive and policy-ready decision-support tool.

5. Conclusion

This study evaluates the cost-effectiveness and sectoral impacts of two carbon optimization strategies in the Nordic forest sector: maximizing carbon storage in harvested wood products (HWP) and maximizing total carbon through avoided harvest in forests combined with HWP pools. A partial equilibrium forest sector model, combined with the Modeling to Generate Alternatives (MGA) method, is used to derive marginal abatement cost (MAC) curves under constrained welfare loss. This approach allows exploration of near-optimal trade-offs between climate mitigation and economic output.

Results show that maximizing total carbon in forest and HWP pools consistently delivers greater carbon gains at substantially lower marginal and average costs compared to the HWP-only strategy. Estimated marginal costs for the combined carbon objective range roughly between €15 to €460 per tCO_2. In contrast, the HWP-focused strategy produces sharply rising costs, reaching up to about €1200 per tCO_2, indicating limited cost-effectiveness at scale. The two strategies also produce contrasting industrial and trade outcomes. While the HWP strategy supports increased harvests and sawnwood exports, it increases dependency on imported sawlogs. The forest-focused strategy depends on sharp harvest reductions, leading to declining domestic wood production and infeasibility beyond 4 % welfare slack. Sensitivity analysis shows that variations in product half-lives and transport costs do not materially alter the relative ranking of strategies. By contrast, assumptions about carbon content and harvest constraints exert a much stronger influence on costs.

Overall, the findings suggest that forest conservation-oriented strategies are more cost-efficient for carbon sequestration than HWP-focused approaches within the NFSM framework, though they entail significant reductions in timber supply and industrial output. The analysis highlights that cost-effectiveness is more sensitive to structural assumptions about carbon content and harvest constraints than to other parameters, a distinction relevant for future policy-oriented modeling. Further research should extend to dynamic settings and incorporate substitution effects to improve robustness and applicability.

Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used Sikt KI-chat in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Junhui Hu: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Eirik Ogner Jåstad:** Writing – review & editing, Supervision, Methodology. **Per Kristian Rørstad:** Writing – review & editing, Supervision, Funding acquisition.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

References

Adams, D., Alig, R., Callaway, J., Mccarl, B., Winnett, S., 1996. The forest and agricultural sector optimization model (FASOM): model structure and policy applications. Introduction. In: US Department of Agriculture, Forest Service, Pacific northwest Research Station, 495, p. 1.

Ahtikoski, A., Rämö, J., Juutinen, A., Shanin, V., Mäkipää, R., 2022. Continuous cover forestry and cost of carbon abatement on mineral soils and peatlands. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.837878.

Bentsen, N.S., 2017. Carbon debt and payback time – lost in the forest? Renew. Sust. Energ. Rev. 73, 1211–1217. https://doi.org/10.1016/J.RSER.2017.02.004.

Bolkesjø, T.F., Trømborg, E., Solberg, B., 2005. Increasing Forest conservation in Norway: consequences for timber and Forest products markets. Environ. Resour. Econ. https://doi.org/10.1007/s10640-004-8248-0.

Bolkesjø, T.F., Trømborg, E., Solberg, B., 2006. Bioenergy from the forest sector: economic potential and interactions with timber and forest products markets in Norway, 21 (2), 175–185. https://doi.org/10.1080/02827580600591216.

Bousfield, C.G., Massam, M.R., Peres, C.A., Edwards, D.P., 2022. Carbon payments can cost-effectively improve logging sustainability in the Amazon. J. Environ. Manag. 314, 115094. https://doi.org/10.1016/J.JENVMAN.2022.115094.

Brill, E.D., Chang, S.Y., Hopkins, L.D., 1982. Modeling to generate alternatives: the HSJ approach and an illustration using a problem in land use planning. Manag. Sci. 28 (3), 221–235. https://doi.org/10.1287/MNSC.28.3.221.

Brunet-Navarro, P., Jochheim, H., Cardellini, G., Richter, K., Muys, B., 2021. Climate mitigation by energy and material substitution of wood products has an expiry date. J. Clean. Prod. 303, 127026. https://doi.org/10.1016/J.JCLEPRO.2021.127026.

Chang, S.-Y, Brill, E.D., Hopkins, L.D., 1982. Efficient random generation of feasible alternative: A land use example. J. Reg. Sci. 22 (3), 303–314. https://doi.org/10.1111/J.1467-9787.1982.TB00754.X.

Chen, Y., Kuang Kirkerud, J.G., Bolkesjø, T.F., 2022. Balancing GHG mitigation and land-use conflicts: alternative northern European energy system scenarios. Appl. Energy 310, 118557. https://doi.org/10.1016/J.APENERGY.2022.118557.

Chiti, T., Rey, A., Abildtrup, J., Böttcher, H., Diaci, J., Frings, O., Lehtonen, A., Schindlbacher, A., Zavala, M.A., Rey, A., Zavala, A., Agroparistech, F., 2024. Carbon Farming in the European Forestry Sector (Doctoral Dissertation,. European Forest Institut. https://doi.org/10.36333/fs17.

Deng, W., Xiang, W., Ouyang, S., Hu, Y., Chen, L., Zeng, Y., Deng, X., Zhao, Z., Forrester, D.I., 2022. Spatially explicit optimization of the forest management tradeoff between timber production and carbon sequestration. Ecol. Indic. 142, 109193. https://doi.org/10.1016/j.ecolind.2022.109193.

Ding, Y., Zang, R., Lu, X., Huang, J., 2017. The impacts of selective logging and clear-cutting on woody plant diversity after 40 years of natural recovery in a tropical montane rain forest, South China. Sci. Total Environ. 579, 1683–1691. https://doi.org/10.1016/j.scitotenv.2016.11.185.

European Commission, 2021, July. New EU Forest Strategy for 2030. https://environment.ec.europa.eu/strategy/forest-strategy_en.

European Commission, 2023. Climate action progress report 2023: tracking progress towards EU climate targets. https://climate.ec.europa.eu/document/download/d0671350-37f2-4bc4-88e8-088d0508fb03_en.

Favero, A., Daigneault, A., Sohngen, B., 2020. Forests: carbon sequestration, biomass energy, or both? Sci. Adv. 6 (13), eaay6792. https://doi.org/10.1126/sciadv.aay6792.

Framstad, E., de Wit, H., Mäkipää, R., Larjavaara, M., Vesterdal, L., Karltun, E., 2013. Biodiversity, carbon storage and dynamics of old northern forests. Nordic Council of Ministers. https://doi.org/10.6027/TN2013-507.

Fuller, M.R., Ganjam, M., Baker, J.S., Abt, R.C., 2025. Advancing forest carbon projections requires improved convergence between ecological and economic models. Carbon Balance Manag. 20 (1), 2. https://doi.org/10.1186/s13021-024-00290-0.

Held, C., Meier-Landsberg, E., Alonso, V., Nacke, J., 2022. *Global Forest Sector Outlook 2050: Assessing Future Demand and Sources of Timber for a Sustainable Economy—Background Paper for the State of the World's Forests 2022.* FAO Forestry Working Paper 31.

Hetemäki, L., Kangas, J., 2022. Forest Bioeconomy and Climate Change (Book), Chapter 1 Forest Bioeconomy, Climate Change and Managing the Change. Spring Nature. https://doi.org/10.1007/978-3-030-99206-4.

Holtsmark, B., 2012. Harvesting in boreal forests and the biofuel carbon debt. Clim. Chang. 112 (2), 415–428. https://doi.org/10.1007/S10584-011-0222-6/FIGURES/5.

Honkomp, T., Schier, F., 2023. Scoping review of carbon pricing systems in forest sector models. Environ. Res. 19, 13001. https://doi.org/10.1088/1748-9326/ad101d.

Howard, C., Dymond, C.C., Griess, V.C., Tolkien-Spurr, D., van Kooten, G.C., 2021. Wood product carbon substitution benefits: a critical review of assumptions. Carbon Balance Manag. 16 (1), 1–11. https://doi.org/10.1186/s13021-021-00171-w.

Hu, J., Jåstad, E.O., Bolkesjø, T.F., Rørstad, P.K., 2023. Impact of large-scale Bio-CCS deployment on forest biomass competition and forest industry production. Biomass and Bioenergy 175, 106896.

Hu, J., Jåstad, E.O., Bolkesjø, T.F., Rørstad, P.K., 2024. The quantification and tracing of leakage in the forest sector in Nordic countries. Forests 15 (2), 254.

Huang, S.K., Kuo, L., Chou, K.L., 2016. The applicability of marginal abatement cost approach: a comprehensive review. J. Clean. Prod. 127, 59–71. https://doi.org/10.1016/J.JCLEPRO.2016.04.013.

Hynynen, J., Subramanian, N., Antón-Fernández, C., Haikarainen, S., Holmström, E., Allen, M., Huuskonen, S., Siipilehto, J., Salminen, H., Lehtonen, M., Andreassen, K., Nilsson, U., 2025. Can extended rotations promote the reconciliation of multiple management goals set for production forests in Nordic countries? Scand. J. For. Res. 1–15. https://doi.org/10.1080/02827581.2025.2481834.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories: Agriculture, Forestry and Other Land Use, Chapter 12 Harvested Wood Products, 4.

Jarre, M., Petit-Boix, A., Priefer, C., Meyer, R., Leipold, S., 2019. Transforming the bio-based sector towards a circular economy-what can we learn from wood cascading? Forest Policy Econ. 110, 101872. https://doi.org/10.1016/j.forpol.2019.01.017.

Jåstad, E.O., 2020. Doctoral thesis: assessments of the future role of bioenergy in the Nordic energy and forest sectors [Norwegian University of Life Sciences, Ås]. https://hdl.handle.net/11250/3053968.

Jåstad, E.O., Bolkesjø, T.F., Trømborg, E., Rørstad, P.K., 2019. Large-scale forest-based biofuel production in the Nordic forest sector: effects on the economics of forestry and forest industries. Energy Convers. Manag. 184 (October 2018), 374–388. https://doi.org/10.1016/j.enconman.2019.01.065.

Jåstad, E.O., Bolkesjø, T.F., Rørstad, P.K., 2020. Modelling effects of policies for increased production of forest-based liquid biofuel in the Nordic countries. Forest Policy Econ. 113 (March 2019), 102091. https://doi.org/10.1016/j.forpol.2020.102091.

Jåstad, E.O., Bolkesjø, T.F., Rørstad, P.K., Midttun, A., Sandquist, J., Trømborg, E., 2021. The future role of forest-based biofuels: industrial impacts in the nordic countries. Energies 14 (8), 1–24. https://doi.org/10.3390/en14082073.

Jåstad, E.O., Nagel, N.O., Hu, J., Rørstad, P.K., 2023. The location and capacity-dependent price impacts of biofuel production and its effect on the forest industry. Silva Fennica 57 (1). https://doi.org/10.14214/SF.23001.

Kallio, A., Markku, I., Dykstra, D.P., Binkley, C.S., 1987. The Global Forest Sector: An Analytical Perspective. John Wiley & Sons.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S., Beach, R., 2008. Global cost estimates of reducing carbon emissions through avoided deforestation. Proc. Natl. Acad. Sci. USA 105 (30), 10302–10307. https://doi.org/10.1073/pnas.0710616105.

Latta, G.S., Sjølie, H.K., Solberg, B., 2013. A review of recent developments and applications of partial equilibrium models of the forest sector. J. For. Econ. 19 (4), 350–360. https://doi.org/10.1016/J.JFE.2013.06.006.

Leskinen, P., Cardellini, G., González-García, S., Hurmekoski, E., Sathre, R., Seppälä, J., Smyth, C., Stern, T., Verkerk, P.J., 2018. Substitution effects of wood-based products in climate change mitigation. European Forest Institute 27. https://doi.org/10.36333/fs07.

Liu, W.Y., Chiang, Y.H., Lin, C.C., 2022. Adopting renewable energies to meet the carbon reduction target: is forest carbon sequestration cheaper? Energy 246, 123328. https://doi.org/10.1016/J.ENERGY.2022.123328.

Luhas, J., Mikkilä, M., Kylkilahti, E., Miettinen, J., Malkamäki, A., Pätäri, S., Korhonen, J., Pekkanen, T.L., Tuppura, A., Lähtinen, K., Autio, M., Linnanen, L., Ollikainen, M., Toppinen, A., 2021. Pathways to a forest-based bioeconomy in 2060 within policy targets on climate change mitigation and biodiversity protection. Forest Policy Econ. 131, 102551. https://doi.org/10.1016/J.FORPOL.2021.102551.

Lundmark, T., Poudel, B.C., Stål, G., Nordin, A., Sonesson, J., 2018. Carbon balance in production forestry in relation to rotation length. Can. J. For. Res. 48 (6), 672–678. https://doi.org/10.1139/CJFR-2017-0410/ASSET/IMAGES/CJFR-2017-0410TAB2.GIF.

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 (11), 1737–1756. https://doi.org/10.1007/S13280-023-01899-0/FIGURES/2.

Mendoza, G.A., 1987. A mathematical model for generating land-use allocation alternatives for agroforestry systems. Agrofor. Syst. 5 (4), 443–453. https://doi.org/10.1007/BF00047178/METRICS.

Mustapha, W., 2016. The Nordic Forest sector model (NFSM): data and model. Structure 55. http://www.umb.no/statisk/ina/publikasjoner/fagrapport/if38.pdf.

Mustapha, W.F., Bolkesjø, T.F., Martinsen, T., Trømborg, E., 2017. Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – effects of feedstock costs and technology learning. Energy Convers. Manag. 149, 368–380. https://doi.org/10.1016/j.enconman.2017.07.004.

Mustapha, W.F., Trømborg, E., Bolkesjø, T.F., 2019. Forest-based biofuel production in the Nordic countries: modelling of optimal allocation. Forest Policy Econ. 103, 45–54. https://doi.org/10.1016/J.FORPOL.2017.07.004.

Myllyviita, T., Soimakallio, S., Judl, J., Seppälä, J., 2021. Wood substitution potential in greenhouse gas emission reduction–review on current state and application of displacement factors. Forest Ecosyst. 8 (1), 1–18. https://doi.org/10.1186/S40663-021-00326-8/FIGURES/4.

Ndjondo, M., Gourlet-Fleury, S., Manlay, R.J., Engone Obiang, N.L., Ngomanda, A., Romero, C., Claeys, F., Picard, N., 2014. Opportunity costs of carbon sequestration in a forest concession in Central Africa. Carbon Balance Manag. 9 (1), 1–13. https://doi.org/10.1186/S13021-014-0004-3/FIGURES/3.

Nordic Council of Ministers, 2023. Nordic economic policy review 2023: EU versus national climate policies in the Nordics. https://pub.norden.org/nord2023-001/nord2023-001.

Price, J., Keppo, I., 2017. Modelling to generate alternatives: a technique to explore uncertainty in energy-environment-economy models. Appl. Energy 195, 356–369. https://doi.org/10.1016/J.APENERGY.2017.03.065.

Reader, R.J., 1987. Loss of species from deciduous Forest Understorey immediately following selective tree harvesting. In Biological Conservation 42.

Richards, K.R., Stokes, C., 2004a. A review of Forest carbon sequestration cost studies: a dozen years of research. Clim. Chang. 63 (1), 1–48. https://doi.org/10.1023/B:CLIM.0000018503.10080.89.

Richards, K.R., Stokes, C., 2004b. A review of Forest carbon sequestration cost studies: a dozen years of research. Clim. Chang. 63 (1), 1–48. https://doi.org/10.1023/B:CLIM.0000018503.10080.89.

Schulte, M., Jonsson, R., Hammar, T., Stendahl, J., Hansson, P.A., 2022. Nordic forest management towards climate change mitigation: time dynamic temperature change impacts of wood product systems including substitution effects. Eur. J. For. Res. 141 (5), 845–863. https://doi.org/10.1007/S10342-022-01477-1/METRICS.

Sedjo, R.A., Sohngen, B., Mendelsohn, R., 2001. Estimating carbon supply curves for global forests and other land uses. In: Discussion Papers. https://doi.org/10.22004/AG.ECON.10663.

Sohngen, B., Mendelsohn, R., 2003. An optimal control model of forest carbon sequestration. Am. J. Agric. Econ. 85 (2), 448–457. https://doi.org/10.1111/1467-8276.00133.

Sohngen, B., Mendelsohn, R., Sedjo, R., 1999. Forest management, conservation, and global timber markets. Am. J. Agric. Econ. 81 (1), 1–13. https://doi.org/10.2307/1244446.

Soimakallio, S., Kalliokoski, T., Lehtonen, A., Salminen, O., 2021. On the trade-offs and synergies between forest carbon sequestration and substitution. Mitig. Adapt. Strateg. Glob. Chang. 26 (1), 1–17. https://doi.org/10.1007/s11027-021-09942-9.

Soimakallio, S., Böttcher, H., Niemi, J., Mosley, F., Turunen, S., Hennenberg, K.J., Reise, J., Fehrenbach, H., 2022. Closing an open balance: the impact of increased tree harvest on forest carbon. GCB Bioenergy 14 (8), 989–1000. https://doi.org/10.1111/GCBB.12981.

Strengers, B.J., Van Minnen, J.G., Eickhout, B., 2008. The role of carbon plantations in mitigating climate change: potentials and costs. Clim. Chang. 88 (3–4), 343–366. https://doi.org/10.1007/S10584-007-9334-4/TABLES/5.

Tanguay, X., Essoua Essoua, G.G., Amor, B., 2021. Attributional and consequential life cycle assessments in a circular economy with integration of a quality indicator: a case study of cascading wood products. J. Ind. Ecol. 25 (6), 1462–1473. https://doi.org/10.1111/JIEC.13167.

Trading Economics, 2024. EU carbon permits. https://tradingeconomics.com/commodity/carbon.

Trømborg, E., Sjølie, H.K., 2011. Data Applied in the Forest Sector Models NorFor and NTMIII.

Trømborg, E., Solberg, B., 1995. Beskrivelse av en partiell likevektsmodell anvendt i prosjektet "Modellanalyse av norsk skogsektor" = : description of a partial equilibrium model applied in the project "modelling the Norwegian Forest sector" - Nasjonalbiblioteket. https://www.nb.no/nbsok/nb/dfa173b8aa13ac2cefa56855a4b96e6a?lang=no.

UNECE, 2011. The European Forest Sector Outlook Study II. 2010–2030. UNECE/FAO, Genova.

Wang, P., Deng, X., Zhou, H., Yu, S., 2019. Estimates of the social cost of carbon: a review based on meta-analysis. J. Clean. Prod. 209, 1494–1507. https://doi.org/10.1016/J.JCLEPRO.2018.11.058.

Widmark, C., Heräjärvi, H., Katila, P., Kurttila, M., Lier, M., Mutanen, A., Øistad, K., Routa, J., Saranpää, P., Tolvanen, A., Viitanen, J., 2020. The Forest in Northern Europe's Emerging Bioeconomy. Reflections on the forest's role in the bioeconomy, Report.

Wu, X., Brüggemann, N., Gasche, R., Papen, H., Willibald, G., Butterbach-Bahl, K., 2011. Long-term effects of clear-cutting and selective cutting on soil methane fluxes in a temperate spruce forest in southern Germany. Environ. Pollut. 159, 2467–2475. https://doi.org/10.1016/j.envpol.2011.06.025.

Yeomans, J.S., 2019. Water resource management using stochastic multicriteria population-based algorithms for producing alternatives. J. Earth Environ. Sci. 7, 179. https://doi.org/10.29011/2577-0640.100179.

Zhang, S., Fang, G., Zhang, D., Ju, M., Zhong, H., 2023. Water resources optimal allocation model for coordinating regional multi-level water resources managers' interests. Front. Environ. Sci. 11, 1152296. https://doi.org/10.3389/fenvs.2023.1152296.