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PAPER

Climate effects of improved growth increments and changing utilization strategies for birch (*Betula spp.*) in Southern Sweden – impact assessment in a life cycle perspective

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Supplementary material for this article is available online

Abstract

The short-term effects of alternative forest production and utilization systems in Sweden are of significant interest for climate change mitigation. For that, fast-growing broadleaved tree species, such as birch (*Betula spp.*), represent one possible avenue because they are already adapted to (hemi) boreal latitudes. Currently, non-improved birch is used as a source for fuelwood and pulpwood, whereas developing improved genotypes with better wood quality could deliver long-lived wood products. However, there is still a lack of climate impact assessments regarding the increments of improved birch and changing uses of birch wood. The aim of this work was to investigate and compare the climate impact of 'traditional/non-improved' birch versus 'improved' birch systems, characterized by a 20% total volume gain through time-dependent life cycle assessment methodology. Changes in the product portfolio from short-lived to long-lived wood products were evaluated. The assessment included biogenic carbon dynamics in living biomass and soil, as well as carbon stored in harvested wood products, greenhouse gas emissions from fossil fuels process in value chains, and potential substitution effects, considered over a fixed rotation length of 50 years at the stand level. A shift towards more long-lived wood products could result in more mitigation potential compared to changing birch genotypes. However, these measures may be combined to achieve additional climate cooling effects as compared to the current use of birch in Southern Sweden.

1. Introduction

With intensified global warming, integrated actions are needed to mitigate anthropogenic greenhouse gas (GHG) emissions and enhance nature-based carbon sequestration through tree species adaptation. Planting and managing forests is a measure that can contribute to mitigating climate change by the natural carbon capture via photosynthesis (IPCC 2014). Among the diversified socio-environmental services and benefits, forests provide economically important harvested wood products (HWP). Accordingly, forests act as a sink of carbon dioxide (CO_2), transferring the sequestered carbon from trees to the pool of HWP and keeping it temporally stored through their lifespans. Moreover, wood products can induce a substitution effect, i.e., avoiding emissions of fossil- or mineral-based materials (Grassi *et al* 2021).

In Sweden the dominant tree species, Scots Pine (*Pinus sylvestris*) and Norway Spruce (*Picea abies*) (SLU 2023), are increasingly suffering under climate change effects (Subramanian *et al* 2019, Youssef *et al* 2023, Eckdahl *et al* 2024). Alternative species diversification, such as using fast-growing tree species, could be part of a more climate-resilient forestry, to ensure more stability, resilience and sustainability in future woody biomass provision (Messier *et al* 2022).

Birch (*Betula spp.)* is a fast-growing indigenous broadleaved species in Sweden. The species has been used as a low value-added product for pulp and energy production (Woxblom and Nylinder 2010). However, in the last decades, there have been directed efforts to drive genetic improvement, aiming for increased production of high wood quality for long-lived HWP (Jansson *et al* 2017, Liziniewicz *et al* 2022). Birch has a great potential for increased production in Sweden, currently representing 13% of the national wood production, which is the most frequently cultivated fast-growing tree species in the country (SLU 2023). In addition, birch is suitable for large-scale implementation in Sweden due to its broad range of adaptations dispersed across different latitudes (Dubois *et al* 2020).

Apart from the potential benefits to forest ecosystems, birch has a substantially shorter rotation period compared to conifer species. Previous research has shown potential for making birch a feasible option for high biomass production (Stener and Jansson 2005), and with the advancements in biotechnology and engineering tools, it could be possible to push the species' potential to be widely implemented in practice (Jones *et al* 2021, Liziniewicz *et al* 2022). For instance, higher added-value uses of birch are already used in some Nordic countries, such as plywood (Luostarinen and Verkasalo 2000) and dissolving pulp for cellulosic fibers in the textile industry (Quintana *et al* 2024).

To assess the overall climate impact of a forest-based value chain, a system perspective should be applied, where changes in forest carbon stock, temporary carbon storage in wood products, value chain emissions, and avoided emissions from substitution of more GHG-intensive materials and energy sources are considered (Schulte *et al* 2022). Life cycle assessment (LCA) is an established method for assessing the climate impact of a product or service throughout its lifespan (ISO 2006). Forestry systems in LCA studies encompass different scopes, functional units, and assumptions, making difficult the comparisons among them. Moreover, using a dynamic LCA is recommended, as it considers the timing of GHG emissions from aforementioned carbon pools, providing a more dynamic overview of the climate impacts and avoiding the underestimation of global warming effects (Garcia *et al* 2020, Wang *et al* 2022).

Different forest management strategies have been extensively studied in climate impact assessments set in Nordic geographies (Kalliokoski et al 2020, Skytt *et al* 2021, Schulte *et al* 2022), including increased yield (Petersson *et al* 2022), as well as the climate effects of varying the wood product portfolio (Hurmekoski *et al* 2020). However, there is still scope for assessing the relative importance for climate change mitigation of the HWP portfolio and forest yield, especially in the role that broadleaved species can play in forestry systems.

The main research question of this work is which option has a better effect on climate change mitigation: (i) increased forest productivity or (ii) changing the HWP portfolio to include different birch genotypes. In addressing this research question, we consider the different carbon pools in standing biomass, soil organic carbon (SOC), HWP, as well as value chain emissions and potential substitution effects.

2. Material and methods

2.1. System boundaries

We applied a stand-level perspective in the present study, assuming two thousand birch (*Betula spp.*) seedlings being planted per hectare (ha). Carbon fluxes assessment was conducted on an annual basis. The geographical location was set in Southern Sweden using mean data from birch yields (current annual increments (CAI) estimations) for both non-improved and improved birch genotypes, which were used for modeling carbon stocks and fluxes in tons of carbon per hectare (Mg C ha^{-1}) in the living biomass (above ground biomass) and SOC. The rotation period was set to 50 years for all scenarios. The first thinning (i) represents 52% of tree removal at the age of 20 years; a second thinning (ii) 59% at 35 years; and a final felling (iii) was done at the age of 50 years based on recommendations of Hynynen *et al* (2010) for birch management. The study period of 100 years was chosen to include two rotations, and to facilitate comparison with similar studies. Additionally, the system boundary encompassed a holistic view of the forestry system, taking into account emissions from both forest and industrial operations, as well as the impacts of harvested wood products (HWP) and potential substitution effects from materials and energy (figure 1).

2.2. Model choice and description

In Sweden, Heureka is a well-established decision support system for forestry that uses tree growth functions, management tools, and other optional features (e.g. carbon sequestration) that can help foresters and researchers to decide which silvicultural practices should be implemented to achieve their goals (Lämås *et al* 2023). Despite being suitable software for Swedish conditions, it is more recommended for regional and

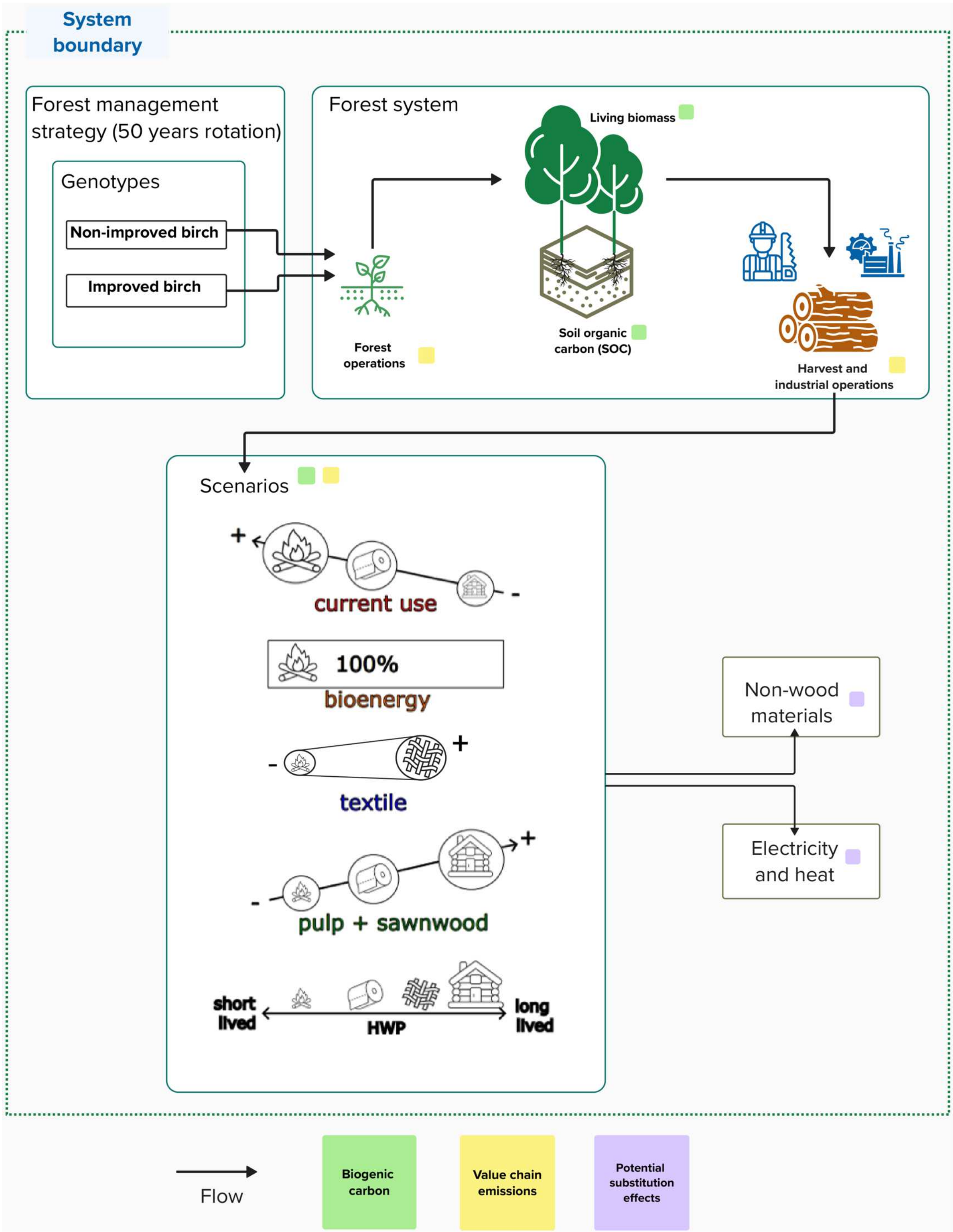


Figure 1. System boundary including forest management strategy, forest system, value chain emissions (VCE), potential substitution effects and harvested wood products (HWP).

national perspectives because it relies on national inventory data of the mixed forest matrix. Instead, we used CO2FIX (Schelhaas *et al* 2009) to overcome those limitations and to allow for more flexibility in choosing site-specific calibration parameters for simulating forest growth and carbon quantification in different pools.

Additionally, for SOC quantification, it also enables using the Yasso model (a Finnish tool for modeling soil carbon), which is more suitable for forest systems than the Q-model used in Heureka (Ågren *et al* 2007). The Q-model is based on broader assumptions (e.g., the same microbial decomposition process for wood and non-woody portions and, no climate parameters interferences) which could limit the SOC dynamics representation in forest systems (Stendahl *et al* 2017).

CO2FIX (version 3.2) is a stand-level carbon dynamic model that uses growth yield curves as the main input (Schelhaas *et al* 2009). Carbon allocation rates to foliage, branches, and roots are considered for estimated litter

Table 1. Roundwood assortments per scenario for non-improved (a) and improved birch (b). Note that each triplet of % values per roundwood assortment class represents (i) first thinning, (ii) second thinning, and (iii) final felling, respectively. Those allocations represent the initial parameters set in CO2FIX.

Scenario	Sawlog			Pulpwood			Fuelwood			Harvesting residues		
	i	ii	iii	i	ii	iii	i	ii	iii	i	ii	iii
						(a)						
Current use (reference)	0%	0%	13%	60%	65%	57%	10%	10%	10%	30%	25%	20%
Bioenergy	0%	0%	0%	0%	0%	0%	70%	75%	80%	30%	25%	20%
Textile	0%	0%	0%	60%	65%	70%	10%	10%	10%	30%	25%	20%
Pulp + Sawnwood	0%	27%	47%	60%	38%	23%	10%	10%	10%	30%	25%	20%
						(b)						
Current use	0%	0%	16%	60%	65%	54%	10%	10%	10%	30%	25%	20%
Bioenergy	0%	0%	0%	0%	0%	0%	70%	75%	80%	30%	25%	20%
Textile	0%	0%	0%	60%	65%	70%	10%	10%	10%	30%	25%	20%
Pulp + Sawnwood	0%	32%	56%	60%	33%	14%	10%	10%	10%	30%	25%	20%

and used further as inputs for the soil module. Effects of tree mortality and harvesting are available options for the simulations. Soil carbon modeling in CO2FIX is performed by the integrated Yasso model (Liski *et al* 2005).

Yasso is a dynamic soil model composed of three litter compartments: non-woody litter (foliage and fine roots), fine woody litter (branches and coarse roots) and coarse woody litter (stem), which are used as inputs from natural or harvesting residues (slashes) considering their turnover rates (leaves, roots and branches). In addition, five decomposition compartments are part of the SOC model: cellulose, extractives, lignin-like compounds, and two types of humus. The model also takes into account meteorological inputs, such as temperature and precipitation, to simulate field conditions of the SOC dynamic. For SOC simulations, the initial parameters were assumed after a steady state of 1000 years—47 Mg C ha^{-1} of a previous forest (spruce) plantation from sample cases of the CO2FIX manual (Schelhaas *et al* 2009). We refer to the Supplementary file for detailed information about CAI estimations (for both non-improved and improved birch), rotation period, and initial setting parameters used for the simulated scenarios.

2.3. Scenarios design

Four scenarios were defined based on potential uses of birch, and two versions of each were assessed (for non-improved and improved genotypes, respectively) as described below.

The reference scenario, denominated *Current use* (non-improved Birch), represents the business as usual when it comes to harvested birch roundwood assortments, i.e., pulpwood and fuelwood, based on Lidman *et al* (2021); in addition, *Current use* (improved Birch) was set by slightly increasing the share of roundwood assortments from pulpwood to sawnwood.

The *Bioenergy* scenarios (non-improved/improved birch) were set as hypothetical scenarios in which most of the harvested woody biomass is assorted to fuelwood. The logic behind it was to assess the climate effect of using the woody biomass exclusively for energy. Further, in times of high energy prices, the price of fuelwood can reach the level of pulpwood (LUKE 2023), which means that all of the harvested biomass could be used for energy. However, the planned energy use would likely shorten the rotation period due to economic considerations.

Long-lived textiles are generally considered to be one of the most promising emerging wood-based markets (Hurmekoski *et al* 2018, Kallio 2021), and thus the *Textile* scenarios (non-improved/improved birch) foresee a change from the traditional use of birch for paper production to textile production (increasing the share of dissolving pulp (100%) to produce viscose).

Finally, the *Pulp + sawnwood* scenarios (non-improved/improved birch) represented the roundwood assortments' assumptions based on Romāns (2022), as potential uses of more long-lived HWP, especially by processing sawlogs with higher wood quality increment provided by the improved material.

Depending on the scenario, roundwood assortments in each thinning varied (tables 1 and 2), to assess the effect of HWP life spans and potential substitution effects. Indeed, improved materials would lead to shorter rotation periods, but we assumed the same rotation and thinning setups for all scenarios to facilitate computations and comparison across scenarios.

We assumed that 30% of harvesting residues were left in the field for decomposition and incorporation as SOC, following the recommendation from Swedish slash management to retain at least 20% of logging residues in the field (Swedish Forestry Agency, 2019). The remaining 70% of harvest residues were used as fuelwood. For

Table 2. Relative change between non-improved and improved birch.

Scenario	Sawlog			Pulpwood			Fuelwood			Harvesting residues		
	i	ii	iii	i	ii	iii	i	ii	iii	i	ii	iii
Current use	1	1	1.23	1	1	0.95	1	1	1	1	1	1
Bioenergy	1	1	1	1	1	1	1	1	1	1	1	1
Textile	1	1	1	1	1	1	1	1	1	1	1	1
Pulp + Sawnwood	1	1.2	1.2	1	0.87	0.61	1	1	1	1	1	1

each scenario, 21, 17.5 and 14% additional fuelwood were accordingly available from (i) first thinning, (ii) second thinning, and (iii) final felling, respectively.

The reference scenario (*Current use*) was using non-improved birch forest for comparison with the other seven forest management scenarios and genotypes, the non-improved and improved birch (+20% of initial CAI). The choice of 20% of genetically improved birch was an average value considering the potential estimations from experiments of Liziniewicz *et al* (2022). All scenarios have a fixed share of harvesting residues and fuelwood (table 1). This means that the *Bioenergy* and *Textile* scenarios have no relative change by comparing their own genotypes because they just have one final product aim, either fuelwood or pulpwood (table 2). However, for the other scenarios, long-lived HWP were prioritized (sawlog assortments), as for both *Current use* and *Pulp + sawnwood* scenarios, and, consequently, the share for pulpwood decreased (table 2).

2.4. Carbon modelling

CO2FIX includes a product module simulating HWP carbon pools. However, here we used the living biomass and SOC outputs as initial parameters for our own modeling of the LCA. A time-dependent LCA was chosen to assess climate impacts (Levasseur *et al* 2013). The output of pools (HWP from thinnings and final felling, SOC and living biomass) in Mg C ha^{-1} was used in our LCA modeling for different scenarios.

Three components were considered along the life cycle of each HWP: first, **biogenic carbon stocks and fluxes** given in standing biomass, SOC, and HWP (from pulpwood, fuelwood, sawlogs assortments). Refer to the Supplementary file (Table S2) for a complete description of the parameters of life span and decay of each HWP used in the calculations of carbon stock and fluxes; second, **fossil value chain emissions (VCE)** occurring along the production of the different HWP. These were assessed from cradle to grave and geographically based on the life cycle inventory data used from Sweden, Europe or Rest-of-the-World from ecoinvent (version 3.11); and third, **potential substitution effects of material and/or energy**, which are based on Schulte *et al* (2022). An exception was made for the textile scenario, which accounts for 100% of the dissolved pulp directed to viscose production instead of sharing it with paper and paperboard production.

Potential substitution effects are commonly expressed in the form of a displacement factor (DF). The DF is based on the relation between a wood product and its respective replaced product in terms of GHG emissions and the amount of wood utilized in each product considering the same functional unit (Sathre and O'Connor 2010). The DF is thus described as:

$$DF_x = \frac{GHG_{\mathrm{non-wood}} - GHG_{\mathrm{wood}}}{WU_{\mathrm{wood}} - WU_{\mathrm{non-wood}}} \tag{1}$$

where the DF of x, a certain HWP end-use, is given in Mg fossil C Mg^{-1} biogenic carbon stored in the wood, and $GHG_{\text{non-wood}}$ and GHG_{wood} represent the GHG emissions from cradle to grave of the substituted non-wood and wood product, respectively, expressed in mass units (mega gram (Mg)) of carbon corresponding to the CO_2-eq of the emissions. WU_{wood} represents the amount of wood used in the wood product, while $WU_{\text{non-wood}}$ indicates the amount of wood used in the substituted product; both are expressed in mass units of carbon. Using equation (1), we calculated the DF for each end-use (table 3) based on the amount of birch HWP and assuming similar potential substitution effects as Schulte *et al* (2022).

To assess the magnitude of potential substitution effects either as carbon sink or source, the market displacement factor DF_m was further calculated (table 3) for each scenario and consisted of the weighted DFs of each HWP end-use assessed similarly as in Hammar *et al* (2020) and Schulte *et al* (2021):

$$DF_m = \frac{\sum_{x=1}^{n} DF_x . W_x}{\sum_{x=1}^{n} W_x} \tag{2}$$

where Wx is the weight, or amount, of each HWP end-use x as a share of the total HWP end-use amount (Hurmekoski *et al* 2021). Note that it is impossible to multiply DF_m with initial harvest volumes, as it is derived

Table 3. HWP allocations and substitution portfolio adapted from Schulte *et al* (2022) and (Hurmekoski *et al* 2020).

HWP	End-use	Replaced product	Functional unit	DF ($Mg\,C\,Mg\,C^{-1}$) per scenario				Reference
				Current use	Pulp + Sawnwood	Bioenergy	Textile	
Sawnwood	Construction	Concrete	Multi-Family Housing Residence	0.68	0.68			Peñaloza *et al* (2016), Mehr *et al* (2018), Piccardo and Gustavsson (2021)
		Steel		0.19	0.19			
	Packaging (Pallets)	HDPE	EU Norm Pallett	−0.45	−0.46			EPAL (2021), APLP (2021)
	Furniture	Steel, PP, PUR, glass, aluminum, PVC	Average Furniture Article	0.47	0.47			Geng *et al* (2019)
	Other	—	—	—	—			
Plywood + Fiberboard	Construction	Gypsum, Mineral Wool, Plaster	Multi-Family Housing Residence	−0.03	0.04			(Peñaloza *et al* 2016), (Mehr *et al* 2018), (Piccardo and Gustavsson, 2021)
	Other	—	—	—	—			
Pulp & paper	Graphical paper	—	—	—	—			
	Paperboard	PET	Average Paperboard Packaging	1.39	1.39			SCB (2022)
	Viscose	Cotton	Mass Based	−0.05	−0.05		−0.05	Peñaloza *et al* (2019)
	Other	—	—	—	—		—	
CHP	Heat & Electricity	Natural Gas	Energy Content Based	1.42	1.42		1.42	Gode *et al* (2011)
Biofuel	HVO	Diesel		0.19	0.23	0.17	0.13	Gode *et al.* (2011), Hallberg et al (2013), Energistyrelsen (2017)
Weighted Average (DF_m)				0.80	0.69	0.17	−0.05	

HWP = Harvested Wood Product, HDPE = High-Density Polyethylene, PP = Polypropylene, PUR = Polyurethane, PVC = Polyvinylchloride, PET = Polyethylene terephthalate, CHP = Combined Heat and Power, DF = Displacement Factor, DF_m = Market Displacement Factor. Refer to the supplementary file for more information.

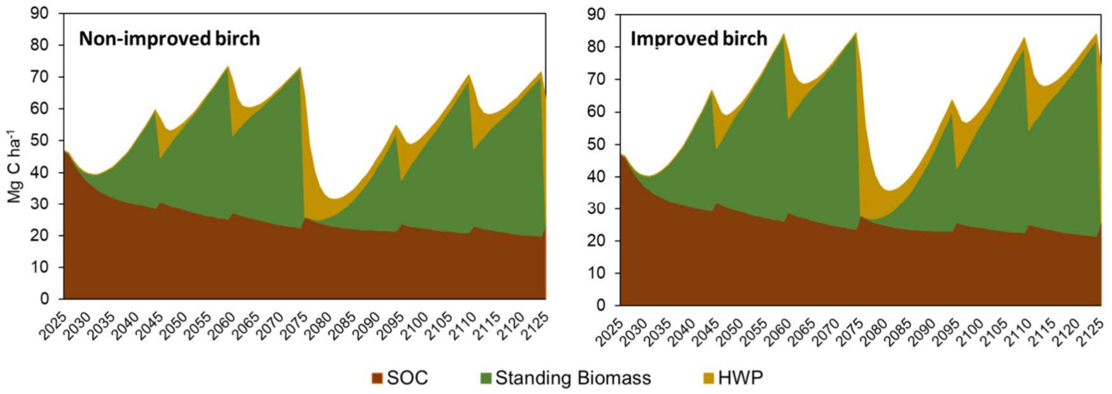


Figure 2. Forest carbon stocks (Mg C ha^{-1}) over 100 years in standing biomass, soil organic carbon (SOC), and harvested wood products (HWP), considering two birch genotypes (non-improved and improved birch) for the reference *(Current Use)* scenario.

from the final HWP end-use amounts. Additionally, to address connected uncertainty and impact on the results, a sensitivity analysis was done simulating an increased and decreased DF_m.

2.5. Climate impact assessment

Here we used the global warming potential for a period of 100 years (GWP_{100}). This method accounts for the cumulative radioactive forcing (CRF), expressed in Wm^{-2}, of a determined greenhouse gas divided by the CRF (Wm^{-2}) of CO_2 and the results are given in carbon dioxide equivalent (CO_2eq) emissions (IPCC 2023). In addition, we used the absolute global temperature change potential (AGTP) expressed in 10^{-10} K ha^{-1} (Boucher and Reddy 2008, Fuglestvedt *et al* 2010):

$$AGTP_x = \int_0^H RF_x(t) \quad R_T(H - t)d_t \tag{3}$$

where radiative forcing (RF) and the climate response function (R_T) form a convolution over the assessed time horizon (H) by a change in the RF from a pulse emission of a specific GHG x. Thus, AGTP, or temperature change (as we refer in the results) accounts for the timing of GHG emissions and their perturbation lifetimes, enabling the assessment of time-dependent climate effects.

3. Results

3.1. Carbon stocks

Overall, living biomass carbon stocks showed a similar pattern for both non-improved and improved birch genotypes, just differing in the amount of carbon due to the 20% volume gain of improved birch. The same pattern was noted for SOC carbon stocks with diminished differences due to the same percentage of carbon harvesting residues that remained in the fields after each felling (figure 2).

Considering the *Current Use* scenario, initially, the living biomass carbon stocks for non-improved birch increased from 31 to 48 and finally 50 Mg C ha^{-1}, before the first, second thinning, and final felling, respectively. For the improved birch, carbon stocks were 37, 57 and 60 Mg C ha^{-1} before the first, second thinning, and final felling, respectively. After each thinning and final felling, most of the carbon was transferred to the temporary HWP pools, excluding the wood process losses, which accounted for 12 to 17 and finally 38 Mg C ha^{-1} right after the first and second thinning and final felling of the first rotation period, respectively. For the improved birch, HWP carbon stocks were 15, 21 and 46 Mg C ha^{-1} right after the first and second thinning and the final felling of the first rotation period, respectively. After each harvest, we had a decrease in this pool due to natural wood decay, considering each specific HWP life span.

Simulated results suggest that SOC levels were 47 Mg C ha^{-1} in each scenario, and over time SOC stocks decreased. After each management intervention (thinnings and final felling), there was a slight increase in SOC due to the remaining 30% harvesting residues left in the field for decomposition. After two rotations (100 years), SOC levels reached nearly 25 Mg C ha^{-1} for both birch genotypes (figure 2). Comparing the relative share of carbon stocks from SOC and living biomass, in the young stand (around 20 years old) SOC represented around 50% of the total carbon pool, and the mature stand (around 50 years old) accounted for 38% of the carbon pool.

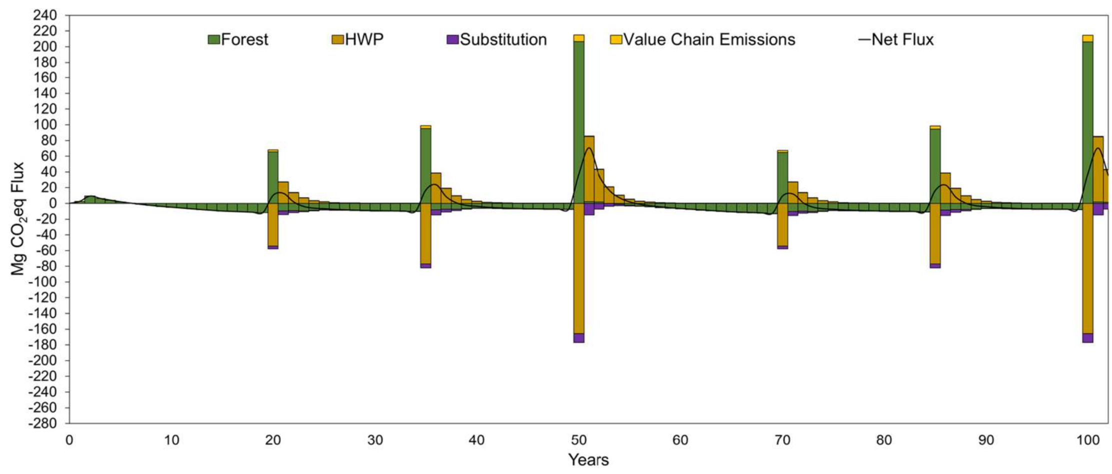


Figure 3. Climate impact in the form of the GWP_{100}. Green bars consider forest pools (standing biomass and SOC). Biogenic carbon includes forest (green bars) and HWP (brown bars). Yellow bars represent value chain emissions (anthropogenic carbon). Purple bars represent the potential substitution effects. The black line is the CO_2eq net flux ($MgCO_2$ ha^{-1}) over a 100-year period considering the *Bioenergy scenario* (improved birch).

3.2. Carbon fluxes and GWP_{100}

Two contrasting scenarios in terms of the life span of HWP, *Bioenergy* and *Pulp + Sawnwood* scenarios for improved birch were used to display the main results of carbon fluxes and GWP_{100} in the forestry system perspective. As a result of the *Bioenergy* scenario of improved birch, in the first six years of forest growth, there were more emissions of biogenic carbon. That was mainly due to the emissions from SOC and the low increment of the initial forest establishment. Afterwards, this trend inverted, and the sink effects of biogenic carbon were more prominent except during the thinnings and the final felling at the end of each 50-year rotation (figure 3).

During the thinnings and the final felling, there was a transfer of biogenic carbon from the standing biomass pool to the HWP pool. The natural decay and short life span of HWP led to a rapid carbon emission into the atmosphere in the subsequent years, primarily due to the brief life span of bioenergy products. VCE had a positive flux of carbon due to the anthropogenic emissions of fossil fuels during forest operations and processing of HWP at the mills. There was also a small potential substitution effect (purple) displayed as a sink effect after each felling and industrial processing (figure 3).

In contrast, the opposite scenario (*Pulp + sawnwood* of improved birch) in terms of longer HWP life span, forest fluxes were the same as previously shown for the *Bioenergy* scenario, because both had the same management strategies: two thinnings (at 20 and 35 years old) and the final felling at the end of each 50-year rotation (figure 4). During the thinnings and the final felling, there is a natural transfer of biogenic carbon from the standing biomass pool to the HWP pool. However, due to the different HWP portfolio, focusing on long-lived HWP rather than the *Bioenergy* scenario (improved birch), the natural decay and life span of HWP has a longer carbon emission that is gradually added to the atmosphere in the following years, but the net flux is decreased by keeping the forest growth in the stand. VCE had a higher carbon emission compared to the *Bioenergy* scenario (improved birch) due to more anthropogenic carbon emissions of fossil fuels during forest operations and processing at the mills of long-lived HWP. Additionally, there was also a higher potential substitution effect (purple) compared to the *Bioenergy* scenario (improved birch), shown as a sink effect after each felling and industrial processing due to material and energy substitution, which compensates for the positive fluxes' emissions of VCE (figure 4).

To demonstrate the potential effects of changing scenarios in terms of GWP_{100} (Mg CO_2eq ha^{-1}), the difference between each scenario and the reference scenario is represented in figure 5. Notice that in some cases there were positive values of potential substitution effects/biogenic carbon and/or negative values of VCE; it is important to point out that these are relative values, resulting from the comparison with the reference scenario.

Considering both genotypes, improved and non-improved birch, the *Bioenergy* and *Textile* scenarios, had positive results of total GWP_{100} compared to the reference scenario. That indicates that those scenarios represent a lower mitigation of climate change due to either higher VCE (*Textile* scenario) or lower potential substitution effects (*Textile* and *Bioenergy* scenarios). In contrast, *Pulp + sawnwood* scenario (non-improved and improved birch) and the *Current use* scenario (improved birch) had a higher mitigation potential (negative results of total GWP_{100}) compared to the reference scenario. Even though VCE was higher in the *Current use*

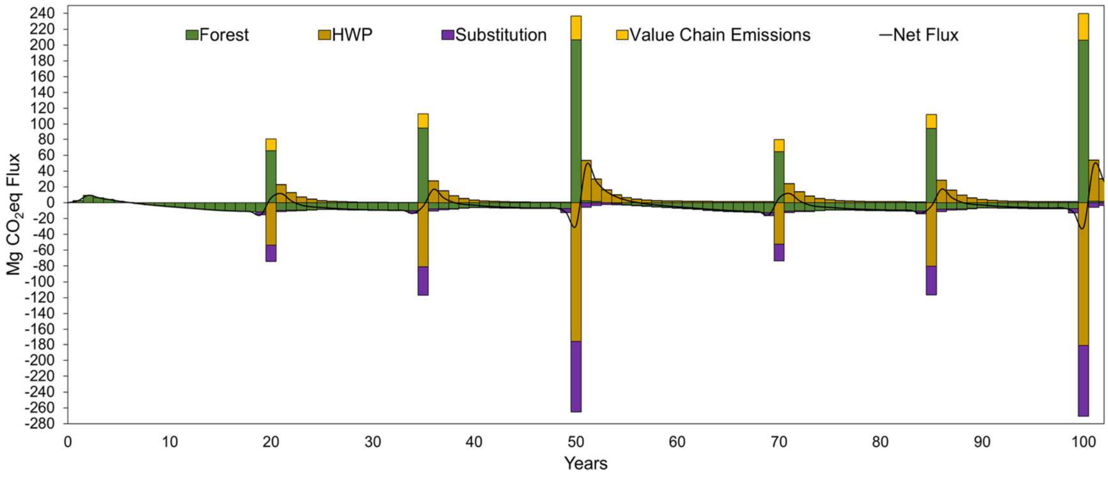


Figure 4. Climate impact in the form of the GWP_{100}. Green bars consider forest pools (standing biomass and SOC). Biogenic carbon includes forest (green bars) and HWP (brown bars). Yellow bars represent value chain emissions (anthropogenic carbon). Purple bars represent the potential substitution effects. The black line is the CO_2eq net flux ($MgCO_2$ ha^{-1}) over a 100-year period considering the *Pulp + Sawnwood* scenario (improved birch).

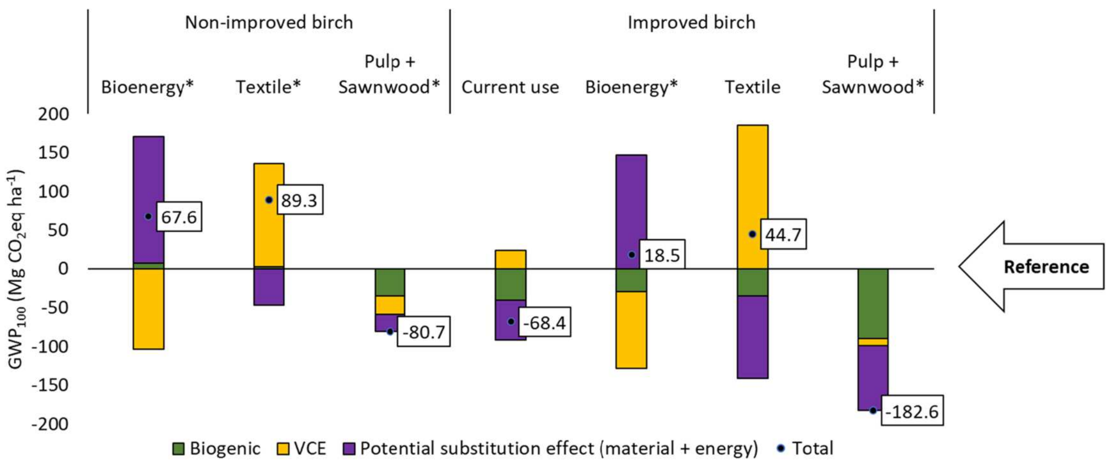


Figure 5. Difference in global warming potential—GWP_{100} (Mg CO_2eq ha^{-1}) for each scenario when compared to the reference scenario over the 100-year time horizon. This includes potential substitution effects (material and energy), value chain emissions (VCE), and biogenic carbon fluxes (standing biomass + SOC + HWP). *Positive values of potential substitution effects/biogenic carbon and/or negative values of VCE mean that the reference scenario had higher values in the designated pool.

scenario (improved birch), it was compensated by their biogenic and potential substitution effects pools (figure 5).

3.3. Temperature change

Regarding the timing of emissions and the potential substitution effects, we obtained similar temporal patterns of temperature change for both improved and non-improved scenarios relative to the reference (figure 6). In terms of average additional mitigation potential, the *Bioenergy* and *Textile* scenarios (both from non-improved birch genotypes), performed worse compared to the reference, representing an additional climate warming until 2125 of $0.12.10^{-10}$ K ha^{-1} and $0.07.10^{-10}$ K ha^{-1}, respectively. In contrast, the remaining scenarios performed better compared to the reference, representing an additional climate cooling until 2125 of $-0.17.10^{-10}$ K ha^{-1} for *Pulp + sawnwood* (non-improved birch), $-0.04.10^{-10}$ K ha^{-1} for *Bioenergy* (improved birch), $-0.09.10^{-10}$ K ha^{-1} for *Textile* (improved birch), $-0.45.10^{-10}$ K ha^{-1} for *Pulp + sawnwood* (improved birch), and $-0.20.10^{-10}$ K ha^{-1} for *Current use* (improved birch).

We refer to the Supplementary file section (Figure S1-S4) for a detailed illustration of each individual HWP scenario (non-improved and improved birch) and to figure S5 for a joint representation of all scenarios.

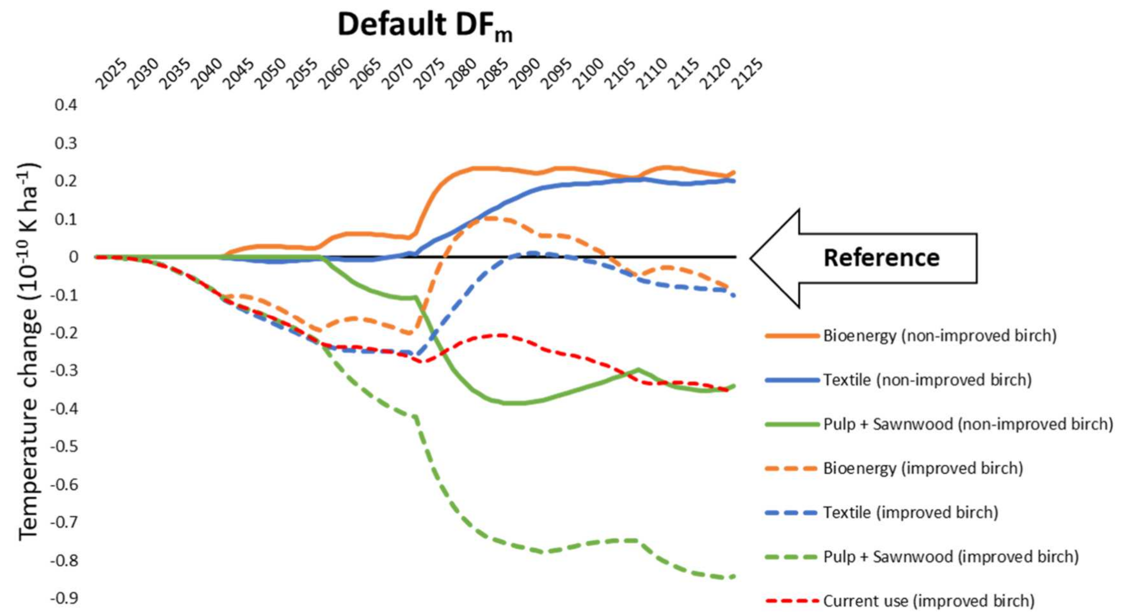
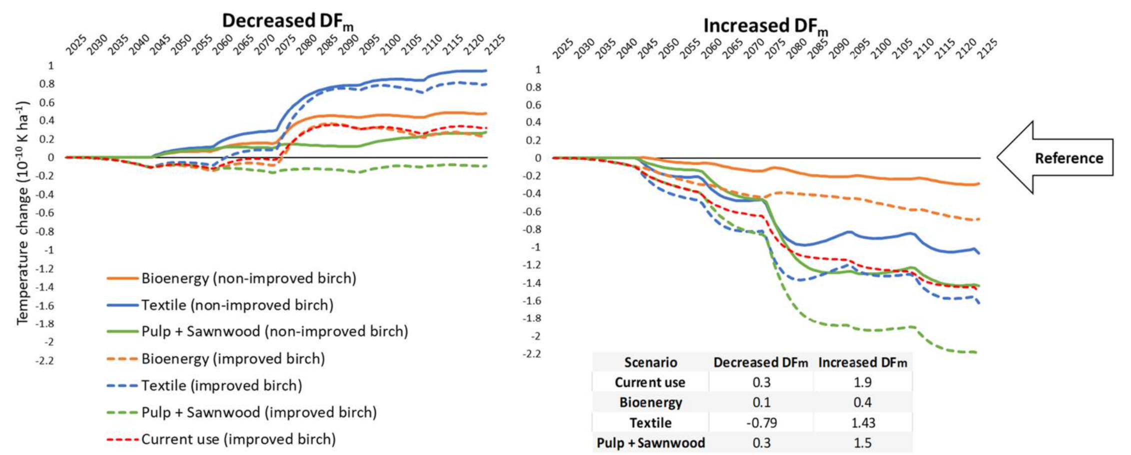


Figure 6. Net difference in temperature change between each scenario compared to reference scenario (*Current use*) over a 100-years period for a default DF_m.



Scenario	Decreased DFm	Increased DFm
Current use	0.3	1.9
Bioenergy	0.1	0.4
Textile	-0.79	1.43
Pulp + Sawnwood	0.3	1.5

Figure 7. Sensitivity analysis of net temperature change difference from each scenario compared to the reference scenario over a 100-year period for decreased DF_m and increased DF_m. Weighted average DF_m for each scenario is displayed in the table on the bottom right.

3.4. Sensitivity analysis

Considering natural changes in the energy mix and manufacturing efficiency performances, it is important to assess the dynamic of modelling scenarios. Therefore, a sensitivity analysis for a decreased and increased DF_m considering the difference of net temperature change from the reference scenario with each other scenario (figure 7) was performed to assess those effects.

In a decreased DF_m, all scenarios compared to the reference will have a warming effect after the beginning of the second rotation period, except *Pulp + sawnwood* scenario (improved birch). In contrast, considering an increased DF_m, all scenarios compared to the reference will have a cooling effect after the first thinning in the first rotation. In that case, changes in the substitution factor will have a higher amplitude and consequently change the ranking of different scenarios compared to the reference scenario. Regardless of the case of decreased or increased DF_m, *Pulp + sawnwood* scenario (improved birch) always had the best climate benefit compared to the reference scenario.

4. Discussion

4.1. Key findings

Considering the dynamic of the temperature changes using the default DF_m, the *Bioenergy* scenario, with lower lifespan and lower substitution effect, has the worst climate performance of all scenarios for a given birch genotype. When using the improved birch genotype, the *Bioenergy* use scenario performs better than the reference scenario in the first rotation period and after the final clear-cut in the second rotation period. This is explained by this wood use scenario having the lowest VCE and the higher carbon increments of improved birch compared to the reference scenario. A similar trend is observed for the *Textile* scenario, despite performing slightly better than the *Bioenergy* scenario from a climate change mitigation perspective, it is still not a climate-efficient option for wood use. In contrast, the *Pulp + sawnwood* scenario had a climate cooling effect for both improved and non-improved birch genotypes, especially due to the longer life span of sawnwood products and higher potential substitution effects (figure 6). Additionally, at the end of the second rotation, the higher carbon increment of improved birch genotypes induces a more prominent cooling effect for all wood use scenarios, even as the VCE tend to be higher due to more wood being processed.

Indeed, the use of improved materials, with higher volume gain and higher wood quality, can also be another strategy aligned to wood production. However, we can still use the option of changing the HWP portfolio while developing new cultivars with the desirable characteristics. A higher increment of long-lived HWPs is an important aspect to consider when striving for climate cooling. As a matter of fact, the *Pulp + sawnwood* scenario (non-improved birch) had a higher cooling effect than other wood use scenarios considering the improved birch genotype. This means that the longer lifespan and the high substitution effect of sawnwood products compensated for the lower volume gain. Previous studies have also stated that increasing the share of long-lived wood products of managed forests can increase the carbon sink effects and, consequently, the climate change mitigation potential by the avoided emission from substituted products (Howard *et al* 2021, Landry *et al* 2021, Gregor *et al* 2024).

4.2. Carbon modelling framework and limitations

The subsequent use of the output data from CO2FIX to estimate carbon fluxes and GWP_{100} presents us a fixed amount of the CO_2eq balance for the specific scenarios as compared to the reference. This is an important step to understand the influence of carbon emissions/sinks of each process in the whole system. However, considering the complexity of the interrelations and dynamics of all subsystems involved (forest, VCE, HWP and potential substitution effects), calculating the temperature change as compared to the reference is a better indicator of climate change over time. Thus, the integration of CO2FIX, carbon modelling, and climate impact metrics could represent an optional framework to be used among other valuable dynamic LCA studies of forestry systems (e.g. in study settings as described in Skytt *et al* (2021), Schulte *et al* (2022), Bozzolan *et al* (2024)).

Overall, the study is limited to the estimation of the climate impacts from a forest stand perspective. Additionally, VCE factors from all processes were derived from average data based on the life cycle inventory from ecoinvent (version 3.11) restricted to the current processing and technology employed for a specific geographic location: mostly Sweden and Europe; in exceptional cases (where data were missing), the Rest-of-the-World average data were used (refer to the supplementary file for detailed information). Thus, any generalization of the results beyond the system's boundaries and assumptions should be carefully considered to avoid misleading interpretation of future perspectives.

4.3. Substitution assumptions and sensitivity analysis

A high degree of uncertainty is generally associated with assumptions on the potential substitution effects due to the dynamic and complex processes of market reality (Schulte *et al* 2022). Hence, it is hard to compare different LCA studies even though they use the same DF equation for assessing HWP substitutions, such as the one stated by Sathre and O'Connor (2010). Calculating DF_m represents a strategy for comparing different scenarios with multiple wood end-uses. As for our results from DF_m considering multiproduct scenarios, e.g., *Current use* and *Pulp + sawnwood*, 0.80 and 0.69, respectively, are in line with other studies (Soimakallio *et al* 2016, Hurmekoski *et al* 2021, Schulte *et al* 2022).

Moreover, the market's complexity and the resulting lack of data for birch limited the level of detail in the assumptions. For instance, we had to assume the same DFs for the sawnwood produced from Norway spruce and birch, despite somewhat different end-uses. Similar assumptions were used in other studies, e.g., in Hurmekoski *et al* (2020). Further, to simplify the analysis, we assumed a constant rotation length, even though it varies with forest productivity and intended use of the wood produced. However, given the notable differences between the different scenarios as to climate impact, changing this assumption would not change the qualitative results.

We expect changes in the ranking of scenarios in the sensitivity analyses, as the calculations of potential substitution effects influence them. One special case is the *Textile scenario* (non-improved and improved birch) that had the highest warming effect due to lower potential substitution effects in the decreased DF_m compared to the reference. Whereas in the increased DF_m, the potential substitution effects and increased carbon increment of *Textile scenario* (improved birch) led to one of the highest cooling effects compared to the reference scenario. Another relevant fact is the *Bioenergy* scenario, which, despite having a slightly better climate benefit than the reference scenario because of lower VCE, had one of the lowest mitigation potentials (cooling effect) compared to other scenarios in the increased DF_m due to the lowest potential substitution effects and shorter life span of fuelwood.

Despite the uncertainties, a future scenario of decreased DF_m is possible and could be attributed to the decarbonization of the energy matrix and processes in the industry sector to align with the Paris Agreement (Niemi *et al* 2025). That effect would result in a lowering of the potential substitution effects from increased use of wood in construction and the manufacture of textile fibers in the short and medium term, as stated by, e.g., Hurmekoski *et al* (2023).

4.4. Challenges of implementing improved birch and transitioning to long-lived HWP

The deployment of genetically improved birch (*Betula spp.)* in Sweden presents both significant opportunities and practical challenges. Genetic improvement programs, relying on provenance trials, seed orchards, and increasingly genomic selection, require considerable long-term investment and higher establishment costs to secure high-quality timber. Protection against browsing is another particularly persistent constraint, making site selection and adaptive silvicultural management decisive for realizing genetic gains (Zvirgzdins *et al* 2025). Opportunely, evidence from Swedish trials demonstrates that improved birch can substantially outperform non-improved birch in terms of growth in Southern Sweden (Liziniewicz *et al* 2022).

It is also relevant to emphasize the significant role that biogenic carbon plays in the temporal dynamics of emissions, especially in longer HWP life spans and consequently in the potential displacement factor of these products, contributing to higher and lasting climate benefits. Long-lived HWP are an important strategy to mitigate climate change, especially in wood utilization in the construction sector. Although, as assumed in the *Pulp + sawnwood* scenarios, converting harvested birch logs into long-lived HWP presents additional technical and logistical challenges. Unlike spruce and pine, birch presents specific challenges in sawing, drying, and grading, requiring mills to adjust their production lines and adopt species-specific standards. Engineered products such as glulam and cross-laminated timber are promising examples, but a consistent log supply of the appropriate dimensions is essential, linking stand management directly to industrial feasibility (Le Pierrès *et al* 2023).

Therefore, a combination of technical, additional economic, and policy barriers further constrain the full adoption of improved birch. From an economic standpoint, high initial costs, coupled with uncertain market demand for birch HWP, make investment risky for landowners and processors alike. Current policy frameworks provide limited incentives to reward carbon storage in long-lived HWP (e.g. the European Union certification framework for permanent carbon removals, carbon farming and carbon storage in products), and the building sector has not fully integrated birch-based engineered wood into their structural standards. Strategies to address these barriers include accelerating breeding cycles through genomic selection (Fugeray-Scarbel *et al* 2024), conducting cost–effective analyses that integrate timber yields with carbon storage and potential substitution effects (Hu *et al* 2025), and developing pilot plantations linked directly to industrial-scale processing trials. Finally, by integrating genetic improvement, adaptive silviculture from existing forestry practices, and targeted policy support, Sweden could expand the role of birch in supplying long-lived HWP, thereby contributing both to forest diversification and to national climate mitigation goals.

5. Conclusion

Changing birch use towards more long-lived wood products with high displacement factors shows a greater potential for mitigating climate change than enhancing birch tree growth by genetically improved genotypes. This conclusion is given when considering a regular market displacement factor and is based on comparing the temperature change of the reference scenario with scenarios assuming other wood product portfolios. For instance, an average additional climate cooling achieves -0.17.10^{-10} K ha^{-1} after two rotation periods, as observed for *Pulp + sawnwood* (non-improved birch) scenario, which brings higher cooling effects than the other scenarios with short-lived wood products considering both genotypes.

Further climate benefits could be obtained by combining genetically improved birch with a shift towards more long-lived wood products (*Pulp + sawnwood* scenario). Uncertainties as to the consequences and impact of climate change (e.g., in form of changes in local precipitation patterns) and future wood prices provide the opportunity to discuss policy measures to increase the production of improved broadleaved species in Sweden.

Gradual change from current dominant conifer tree species towards more broadleaved tree species diversification in Sweden is a challenging topic that deserves more attention. Birch, as a fast-growing tree species already adapted to Swedish biophysical conditions, can represent potential for contributing to climate change mitigation, but more research needs to address the climate impacts of such substitution between tree species. Finally, genetic improvement of birch is necessary to allow enhanced wood quality, which is apt for long-lived wood products to compete with current Norway Spruce and Scots Pine alternatives.

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Conflict of interest

The authors declare no conflict of interest.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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