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Increasing global wood demand will risk forest sustainability

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ABSTRACT

The European Union aims to be climate neutral by 2050, driving ambitious mitigation efforts. Our study investigates how climate and bioeconomy policies impact biodiversity in Sweden. Using GLOBIOM Model, we project the wood demand under three policy scenarios: Current policy, Bioenergy and Bioeconomy. Focal biodiversity indicators are mean deadwood volume, area of old forest, area of old forest rich in broadleaves and mean age of standing trees. Forest dynamics are simulated using Heureka-Planwise. We identify management strategies balancing economic objectives with biodiversity, employing both intensive and extensive approaches. Mean deadwood volume increased substantially in set-asides in all policy scenarios, while in production landscape, nearly tripling under Current Policy scenario and doubled under Bioenergy and Bioeconomy scenarios. The area of old forest on production land declined drastically, reaching 0.1 million ha in Bioeconomy scenario by 2100. Optimization favored intensive management strategies, particularly Bioenergy extraction in Bioenergy and Bioeconomy scenarios. Under Current policy, both intensive and extensive management strategies were equally dominant. Management strategies like Continuous cover forestry and Unmanaged were the least implemented. Wood demand consistently increased across scenarios, stabilizing under the Current policy scenario after 2040. In the Bioeconomy scenario the demand continued to increase, surpassing supply potential by 2070.

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Introduction

As per the 2015 Paris agreement, the participating countries should take measures to restrict global warming by 2°C and continue efforts to limit warming to 1.5°C by the end of this century (UNFCCC 2015). Mitigation efforts involving drastic cuts in greenhouse gas (GHG) emissions from fossil fuels will be required to meet this target. The EU has a target to reduce its GHG emissions by at least 55% below 1990 levels by 2030 and to become climate neutral by 2050 (European Commission 2019). However, the effects of these societal targets on different land-use sectors are poorly understood.

Forests play a key role in the mitigation efforts as they provide wood biomass, which is the primary source of renewable material and energy (Van der Hoeven and Houssin 2015; IPCC 2019), and can also be used for substituting products based on fossil fuels (Lundmark et al. 2014; Smith et al. 2016). Both of these strategies support the shift towards a future bio-based economy (Kraxner et al. 2017). European harvest levels have indeed increased in the last decade (Ceccherini et al. 2020), resulting from the expansion of the wood market and are predicted to increase further due to the ambitious bio-economy policy goals. For Sweden, Nordström et al. (2016) estimated that the demand for wood might increase by up to 30 million m^3 yr^{-1} (38%) between 2010 and 2090. However, decreasing harvests and storing carbon in the forest has been suggested as a wiser strategy, as the use of forest bioenergy accelerates climate warming (Reid et al. 2020). Moreover, recent reviews have concluded that current reductions in forest carbon if increasing harvesting is higher than the avoided fossil emissions from carbon

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sequestration (removal) in harvested wood products and geological storage (Hurmekoski et al. 2021; Soimakallio et al. 2021). Moreover, displacement factors and future rate of substitution are very uncertain (Niemi et al. 2025), but if societies decarbonize, displacement factors and substitution rates should decrease.

Old forests are a key indicator of biodiversity. The largest share of the world's old forest (defined as those older than 150 years) is located in the boreal and temperate regions (Mackey et al. 2015; Mönkkönen et al. 2022). A reduction in the area of old forests with large trees will have major negative impacts to ecosystem process and species depending on them. Intensive forest management has considerably reduced the area of old forests, and the remaining old forests are scattered among the younger stands due to the dominant even-aged management in Nordic countries (Kuuluvainen and Gauthier 2018). The decline of old forests has adverse effects on the structural forest diversity, such as lack of big and old trees (Mönkkönen et al. 2022), large snags and large standing and downed deadwood (Kuuluvainen 2009). Old forests in the boreal region are projected to decrease due to increased harvest levels and changes in disturbance regimes (Bergeron et al. 2017; Ahlström et al. 2022). As a result, there will be a loss of biological and structural diversity, also reducing ecosystem resilience (Kuuluvainen 2009; Venier et al. 2014; Gauthier et al. 2015). Broadleaved forest, particularly old forest rich in broadleaves have also decreased considerably in southern Sweden due to intensive forest management (Lindbladh et al. 2014; SLU 2018). Around one-fourth of the forest-dwelling species in boreal Fennoscandia depend on deadwood, and they constitute around 60% of the red-listed species (Siitonen 2001). Currently, the deadwood volume in Finnish (Korhonen et al. 2021) and Swedish (Skogsstyrelsen 2018) forest is well below 10 m^3 ha^{-1}, while under natural conditions, the volume can be up to 120 m^3 ha^{-1} (Siitonen 2001; Rouvinen et al. 2002). Many threatened species occur only in forests with at least 20–40 m^3 ha^{-1} of deadwood (Müller and Bütler 2010). Nevertheless, the deadwood volume in the forest landscape is projected to increase due to the increase in tree mortality as a result of climate change (Peng et al. 2011; McDowell and Allen 2015). But this trend may be applicable to small sized trees as they are more prone to self-thinning.

It is crucial to maintain enough of old, mixed, unmanaged and uneven-aged forests in the landscape to safeguard biodiversity, ecosystem services and functions (Kuuluvainen and Gauthier 2018; Peura et al. 2018; Mazziotta et al. 2022; Moor et al. 2022). It has been suggested that by careful forest management planning, the negative impacts of wood harvest on biodiversity and ecosystem services can be decreased (Eyvindson et al. 2021; Moor et al. 2022). Thus, a change in the current management practice may improve the conditions for biodiversity and ecosystem services of boreal forest (Eggers et al. 2022).

The structure and composition of forests are impacted differently by various management strategies. Intensive management reduces both presence of individual species (Belinchón et al. 2017, Mair et al. 2018) and key habitats for biodiversity (Felton et al. 2017; Eggers et al. 2020). Intensive forest management for wood production and increased harvest levels result in biodiversity loss, a reduction in old forests with large amounts of deadwood, the expansion of monocultures and adverse effects on soil erosion and water regulation, among others (Gauthier et al. 2015; Alrahahleh et al. 2017; Heinonen et al. 2018; Ceccherini et al. 2020). To preserve biodiversity at landscape level, this needs to be combined with protecting forest or adopting extensive management strategies.

Currently, the production forest in Fennoscandia predominantly consists of even-aged stands, regenerated by planting, regular thinning and clear-felling at around 60–120 years of forest age. Pang et al. (2017) showed that applying Continuous Cover Forestry (CCF) in the whole landscape will improve the habitat availability for key bird species, but it might reduce the total harvests by 30%. However, studies also show that the net present value (NPV; NPV is the difference between present value of all future cash inflows and outflows over a period of time) of applying CCF can be higher in landscapes dominated by Norway spruce *(Picea abies (L.) Karst.)* than even-aged clearcutting management and harvested volumes may not be severely reduced (Peura et al. 2018; Eggers et al. 2020; Pukkala 2021). Prolonged rotation lengths may increase the forest's carbon stock, but it will decrease the yield (Lundmark et al. 2018). Adapting intensive management strategies like shortening the rotation length by avoiding thinning may increase the forest resilience against natural disturbances (Hahn et al. 2021). However, these management strategies may adversely affect biodiversity and ecosystem services (Subramanian et al. 2016; Lucash et al. 2017). About 20% of the harvest residues are extracted in Sweden, while stump harvest is applied at a trial stage (de Jong et al. 2017), but may increase in the future. In Finland, approximately 3 Mm^3 of harvesting residues is used annually for energy (LUKE 2021). However, if slash and stumps are harvested on more than 80% and 30% of the annual final felled area, respectively, there might be adverse effects on wood production and biodiversity (de Jong et al.

2017). Even though extending the rotation length by 50% positively influences species requiring old forests, thus promoting biodiversity (Belinchón et al. 2017), it may reduce the NPV by 19% and harvested volume by 13% (Roberge et al. 2018).

The overall aim of this study is to investigate how climate change mitigation and bioeconomy policies on different spatial scales may affect future harvest levels, management and key biodiversity indicators in Sweden. More specifically, given scenarios assuming different climate mitigation and bioeconomy policies, we estimate the future demand of wood assortments from Sweden and investigate how meeting the demand may change future levels of key indicators of biodiversity. We further investigate whether the future development of the indicators will be different between land used for production and for set-aside. Using an advanced decision support system together with global demand for wood from Sweden we identified the optimal combination of management strategies maximizing NPV constrained to meet the demand for different wood assortments given different policies and bioeconomic development. Finally, we explore how meeting future demand for wood assortments affect future forest management by analysing the identified optimal management strategies.

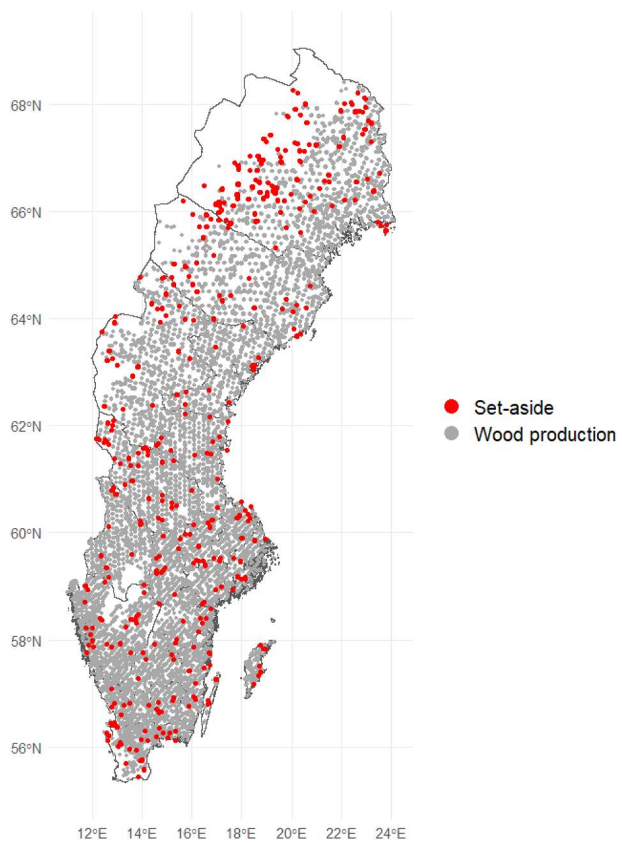

Figure 2. Map of Sweden showing the location of the 30,000 National Forest Inventory (NFI) plots in production forest area studied.

Materials and methods

Study area

This study was conducted in the boreal forest of Sweden which is composed of approximately 80% conifers, such as Scots pine (*Pinus sylvestris L.*) and Norway spruce *(Picea abies (L.) Karst.), and 12% birch (Betula spp)*. The dominance of conifers is mainly due to the prevailing forestry practice that focuses on planting conifers after clear cutting. After planting the stands undergo one pre-commercial thinning and up to three commercial thinnings before clear cutting. Typical rotation age is around 70–150 years, and the shortest rotation occurs in southern Sweden.

We used the nation-wide forest dataset from the Swedish National Forest Inventory (NFI) and the surveys of forest soils and vegetation. The inventory uses a regular sampling grid with a randomly selected starting point covering the whole country. The NFI consists of a systematic network of around 30,000 circular permanent and temporary sample plots in clusters called tracts spread across productive forest land in Sweden (Fridman et al. 2014). Permanent sample plots are re-surveyed once every 5 years. Each sample plot has a unique plot id and a radius of 10 m (permanent plots) or 7 m (temporary plots). The tracts, which are rectangular in shape and are of different dimensions in different parts of the country, consist of 8 (in the north) to 4 (in the south) circular sample plots. We used the site and stand data obtained from the NFI measurements conducted on productive forest land (defined as land with a potential yield capacity of 1m^3 mean annual increment per hectare on average over 100 years) during the period 2008–2012 (Figure 2).

Simulation of the global demand for wood from Sweden using GLOBIOM-EU

The global demand for wood from Sweden was estimated using GLOBIOM-EU which is a version of the partial equilibrium model GLOBIOM (Havlík et al. 2014), developed by the Institute of Applied System Analysis (IIASA). GLOBIOM-EU can simulate and project the development of the silviculture and bioenergy sectors worldwide (Frank et al. 2015). This dynamic optimization tool allows adjustments in production, international trade and commodity movement to meet the global demand for final products. At the EU-level, the trade flows are simulated with higher accuracy, e.g.

geographic maps and processing of commodities used in each EU member state are represented with the highest available spatial resolution in GLOBIOM-EU. These trade flows are balanced among the geographical regions based on cost competitiveness and bilateral trade flows (Frank et al. 2015). The global spatial dynamics of wood flow projected by GLOBIOM-EU, considering socio-economic development serve as an input for the geographically explicit forest management model G4M (Kindermann et al. 2008; Gusti 2010). G4M simulates the development of forest area and the dynamics in forest management activities as a response to scenario-specific wood demand and a series of forest resource constraints (Figure 1). The harvest potentials are calculated considering spatially explicit harvest, transportation and land-use change cost. The GLOBIOM-EU time step is ten years. The socio-economic development scenario considered was SSP2 (Figure 1). The Shared Socio-economic Pathways (SSPs) describe alternative future developments of societies and natural ecosystems over a century time scale (O'Neill et al. 2017). SSP2 is the "middle of the road" scenario that predicts a moderate level of sustainable development, technological advancement and inequality in the world.

Total industrial round wood demand (M m^3 yr^{-1}) and demands for different wood assortments such as sawn timber (Mm^3 yr^{-1}), pulpwood (Mm^3 yr^{-1}) and primary source of energywood (Mm^3 yr^{-1}) from Sweden were simulated using GLOBIOM-EU. The primary source of energywood consists of wood biomass directly harvested from forests. This includes logging residues, roundwood rejected by the timber and pulp industries, and stemwood used for burning (Table 1). The simulation period covered the years 2010–2100.

Projections of national forest management and dynamics using Heureka

We used Heureka-Planwise (version 2.11.1.0) for simulating forest management and dynamics. Heureka is an advanced Decision Support System (Lämås et al. 2023), used by many large forest companies in Sweden and has a growth simulator along with a built-in optimizer. The growth simulator includes a set of empirical models for tree growth and establishment, in-growth and mortality of the commercially important tree species (Fahlvik et al. 2014; Eggers et al. 2018). All these are regression models fitted to data from the National Forest Inventory (NFI; Fahlvik et al. 2014). The system allows the user to generate different treatment programs for each treatment unit, e.g. all NFI plots in a country (Figure 2). These treatment programs differ in the type of management system and/or the timing of the silvicultural practices implemented for each unit. Forest management systems like even-aged, uneven-aged or Continuous Cover Forest (CCF) and unmanaged can be simulated along with the set of silvicultural practices like soil scarification, type of regeneration, type of thinning, final felling, fertilization, etc. After the simulation of a large number of treatment programs, the optimizer identifies the optimal combination of treatment programs for each unit given the specified objective and constraints using linear programming (LP) (Figure 1). The management strategy allocated to a particular NFI plot will not change in the middle of the simulation. Forest stand data, including tree species type, diameter at breast height (DBH), height of sample trees, age and stand density from the NFI dataset, were imported into the Heureka software, along with site characteristics such as site index, latitude, altitude, type of ground vegetation, soil depth, soil texture and moisture content.

Climate scenarios

We considered two climate scenarios (Representative Concentration Pathways; RCPs): RCP8.5 and RCP4.5, as implemented in Heureka (Figure 1). The climate scenarios were adopted from the intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) (IPCC 2014). RCP8.5 is the worst-case scenario that predicts an increase in the global mean air surface temperature by 2.6–4.8°C by the end of this century relative to levels in 1986–2005 (IPCC 2014). RCP4.5 is a more optimistic scenario that predicts an increase in the global mean air surface temperature by 1.1–2.6°C. We tested the sensitivity of various climate scenarios in combination with wood demand scenarios on the total standing volume of forest in Sweden. RCP8.5 and RCP4.5 climate scenarios implemented in Heureka are based on General Circulation Model MPI-ESM downscaled for Sweden using Swedish Meteorological and Hydrological Institute's Regional Climate Model (Eriksson et al. 2015a).

Three scenarios of climate change mitigation affecting global wood demand

Three scenarios of global demand for wood from Sweden were simulated using the GLOBIOM-EU model. The scenarios were: (i) Current Policy scenario, (ii) Bioenergy scenario and (iii) Bioeconomy scenario.

The Current Policy scenario was based on the current EU-2020 climate and energy package (European Commission 2012), specifically a 20% reduction in GHG emission by the year 2020 when compared to the emission

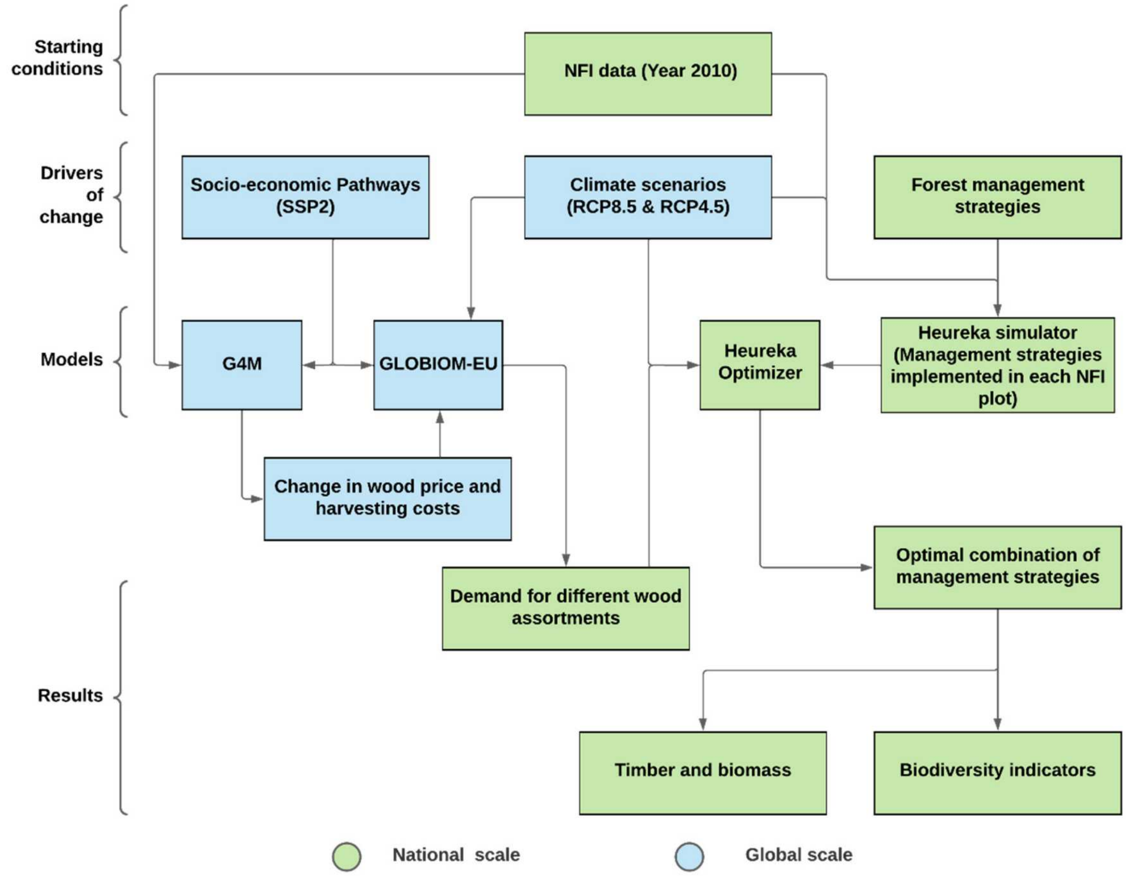

Figure 1. Schematic illustration of our projections of forest management strategies balancing economic outcomes with biodiversity indicators combining GLOBIOM-EU and Heureka models. GLOBIOM-EU projects the development of silviculture and bioenergy sectors worldwide and Heureka simulates the forest dynamics under various management strategies and climate scenarios.

levels in the year 1990 (Capros et al. 2013). No further emission cut targets beyond 2020 were assumed. The share of renewable energy was around 24% by the year 2030 and 29% by the year 2050 (Capros et al. 2013). The demand for woody biomass grew significantly until the year 2020 and later on grew at a slower pace. There was no substantial contribution to emission cuts from non-EU member countries (Capros et al. 2013). The low mitigation actions of this package led us to assume the RCP8.5 climate scenario.

Table 1. List of variables and indicators used in this study.

Variable or Indicator	Definition
Wood assortment variables	
Sawn timber (Million m^3 yr^{-1})	Timber with a minimum length of 340 cm and a maximum length of 550 cm. Minimum diameter at the top 12 cm.
Pulpwood (Million m^3 yr^{-1})	Wood with a minimum length of 270 cm and a maximum length of 550 cm. The minimum diameter at the top is 5 cm.
Energywood (Million m^3 yr^{-1})	Logging residues and wood which are not categorized as sawn timber or pulpwood.
Biodiversity indicators	
Area of old forests (ha)	Area of forests with a minimum age of 140 years in northern Sweden and 120 years in southern Sweden (Nordström et al. 2016).
Area of old forest rich in broadleaves (ha)	Area of forests with a minimum of 25% proportion of broadleaves and with a minimum age of 80 years in northern Sweden and 60 years in southern Sweden (Nordström et al. 2016).
Deadwood volume (m^3 ha^{-1})	Total volume of standing and lying deadwood present in the stand.
Mean age of standing trees	Mean age of all the standing trees in the forest stand.

The Bioenergy scenario assumed that the EU sets forth more stringent and long-term strategies for reducing GHG emissions to restrict the future increase of mean global air temperature to below 2°C by the end of this century (European Commission 2012). Higher GHG emission reduction targets were assumed beyond 2020 compared to those under the Current Policy scenario. The targets on emission reductions were 40% by 2030 and 80% by 2050 compared to the 1990 levels (Frank et al. 2016). The share of renewable energy resources by 2030 was 27%. The targets were assumed to be restricted only to EU member countries while in the rest of the world the targets were similar to those in Current Policy. We assumed that the mitigation actions were effective and therefore assumed the RCP4.5 climate scenario.

Global efforts to reduce GHG emissions beyond 2020 were also considered in the Bioeconomy scenario. We assumed that they followed the recommendations of the 2015 global mitigation scenario (Labat et al. 2015), specifically a 10% reduction by 2030 compared to 2010 emission levels and a 50% reduction by 2050 compared to the emission levels of 1990. The share of renewable energy in this scenario was expected to increase by 20% in 2030 and 40% in 2050 (Labat et al. 2015). For EU member states, we assumed targets as in the Bioenergy scenario. We assumed that also these mitigation actions were effective and therefore assumed the RCP4.5 climate scenario.

Table 2. Description and objectives of the management strategies.

Management strategies	Acronym	Objective	Description
Intensive management strategies			
Bioenergy extraction	BioE	Intensive forest management for energywood production	Management settings similar to CurrMan; Slash extracted during thinning and final felling.
Bioenergy with stump extraction	BioEStump	Intensive forest management with stump extraction	Management settings similar to BioE; slash and stumps extracted during final felling.
Unthinned management	UnThin	Intensive forest management speeding up final felling	Management settings similar to CurrMan; No commercial thinnings; final felled earlier.
Extensive management strategies			
Continuous Cover Forestry	CCF	Forest conservation with limited management	Un even-aged management system; no extraction of logging residues (Implemented only in spruce dominated stands).
Promoting broadleaves	BroadL	Promote broadleaves	Management settings similar to CurrMan; Broadleaves were retained during final felling as seed trees; Conifers were removed during thinning and cleaning.
Extending the rotation length	ExtRot	Postpone final felling	Management settings similar to CurrMan; Final felling was extended by 30–50 years after Lowest allowable final felling age if needed.

Simulation of forest management strategies using Heureka

Each NFI plot was linked to a set of predefined forest management strategies that varied in the type and the timing of silvicultural practices for simulation. The simulation period was 90 years divided into 18 five-year periods (2010–2100). Legally protected national parks and nature reserves were left unmanaged, constituting around 3.6% of the total productive forest area in Sweden (Figure 2). On the production land, we simulated eight management strategies, a current management strategy (CurrMan), three intensive strategies and four extensive strategies (Table 2). The intensive strategies were (i) Bioenergy extraction (BioE), (ii) Bioenergy with stump extraction (BioEStump) and (iii) Unthinned management (UnThin). The extensive strategies were (i) Continuous Cover Forestry (CCF), (ii) Promoting Broadleaves (BroadL), (iii) Extending rotation length (ExtRot) and (iv) Unmanaged (UnMan). CCF was applied only to NFI plots dominated by Norway spruce (*Picea abies (L.) Karst*) because CCF is recommended only in Norway spruce dominated stands.

The CurrMan followed the prevailing forest management practice in Sweden. It is an even-aged clear felling system with pre-commercial thinning and up to three commercial thinnings before final felling. We used the default management settings in Heureka, except for also extracting logging residues during final felling in stands dominated by Norway spruce and Scots pine. To avoid the reduction in forest productivity due to extracting logging residues, slash and stumps were extracted on 70% and 30% of the total annual area final felled, respectively (de Jong et al. 2017). Final felled areas were regenerated using hybrid saplings. During final fellings, three high stumps ha^{-1} and ten living trees ha^{-1} were left as retention trees.

Wood prices were obtained from the forest owners' association Mellanskog (Mellanskog 2016). For calculating Net Present Value (NPV), we assumed a discounted interest rate of 2% that was applied to future costs for silvicultural operations and incomes obtained from the forest. We assumed different climate scenarios (RCP8.5 and RCP4.5) for different wood demand scenarios, (see *Heading* below).

Optimization of management strategies

We used linear programming to identify the optimal combination of treatment programs across the country. For each five-year period, the demand for wood assortments (sawn timber, pulpwood and energywood) projected by GLOBIOM-EU was set as target harvest levels in Heureka (Figure 1). The harvested volume was classified into different wood assortments in Heureka based on the tree diameter (Table 1) and the price list. The objective function was to maximize NPV. For each of the three scenarios, we calculated the percentage of area covered by each management alternative across the country. The mathematical formulation used in Heureka's optimizer is provided in the Suppl. Material S3.

Estimation of the potential supply of wood from Sweden

The potential supply of wood from Sweden under future climate scenarios such as RCP4.5 and RCP8.5 were simulated using Heureka. The highest possible harvest levels under the condition of sustainable yield were used to estimate the potential supply. This means that the allowed annual harvest was equal to the yearly growth. Potential supply under the RCP8.5 climate was considered as the maximum harvest level possible satisfying the conditions of sustainable yield in the Current Policy scenario. Whereas the potential supply under the RCP4.5 climate scenario was regarded as the maximum harvest level possible under conditions of sustainable yield under the Bioenergy and Bioeconomy scenarios. The potential supply was included in the study to analyze whether the demand for wood from Sweden surpasses the potential supply level. We assumed that if the demand for wood from Sweden surpasses the potential supply, then extracting wood from the forest will become unsustainable.

Environmental impacts of the chosen management strategies

We considered four biodiversity indicators for analyzing the environmental impacts of the chosen management strategies. Biodiversity indicators considered in this study were (i) mean deadwood volume (m^3 ha^{-1}), (ii) area of old forests (Mha), (iii) area of old forests rich in broadleaves (Mha) and (iv) mean age of standing trees (Table 1). Intensive forestry in Fennoscandia has decreased the amount of deadwood, old forest area, and broad-leaved tree dominated forests, all of which are critical characteristics for biodiversity in boreal forest (Siitonen 2001; Vanha-Majamaa et al. 2007; Mönkkönen et al. 2022). The biodiversity indicator variables for each NFI plots were calculated and later, the individual plot variables were summed up for estimating the value for the whole forest landscape in Sweden. The impact of different global demand scenarios for Swedish wood on these biodiversity indicators was analyzed in wood production and set-aside areas separately. A further analysis was conducted to identify the combination of management strategies along with wood demand scenarios and climate scenarios that had the largest effects on mean volume of deadwood, mean standing volume, mean standing volume of broadleaves, mean age of standing trees and age-class distribution of the trees (See Suppl. Material S1 for details).

Results

Global demand and supply potential of wood

The demand for wood increased in all the three scenarios (Figure 3). In the Current Policy scenario, the increase stabilized after 2040. However, in the Bioenergy and Bioeconomy scenarios, the demand steadily increased until the end of the simulation period. Total demand was higher in the Bioenergy scenario than in the Current Policy scenario, mainly due to increased demand for energywood. In the Bioeconomy scenario, this increased demand became very prominent after 2060, again predominantly due to a high demand for energywood (Figure 3). In this scenario, the total demand even surpassed the sustainable supply potential by 2070 (Figure 3). This high demand led to burning sawn timber and pulpwood (See Suppl. Material S4 Figure S6). Until 2050 the energywood supply matched the demand, but thereafter the energywood demand steadily increased until 2100 when the deficit was 12 million m^3 yr^{-1}. This led to a parallel increase in use of timber and pulpwood for energy reaching 16% in 2100 (See Suppl. Material S4).

Standing volume

Starting from 2010, the standing volume increased in the Current Policy and Bioenergy scenarios, but not in the Bioeconomy scenario where it diminished after 2070 (Figure 3). The highest volume increase was in the Current Policy scenario, where it more than doubled (227%) by the end of the simulation period. In the Bioenergy and Bioeconomy scenarios, the standing volume increased by 176% and 130%, respectively, by the end of the simulation period (Figure 4).

Mean deadwood volume

The mean deadwood volume increased considerably in all demand scenarios, especially in the forest set-aside from production (Figure 5). In the set-asides the deadwood density increased from 21 m^3 ha^{-1} to about 50

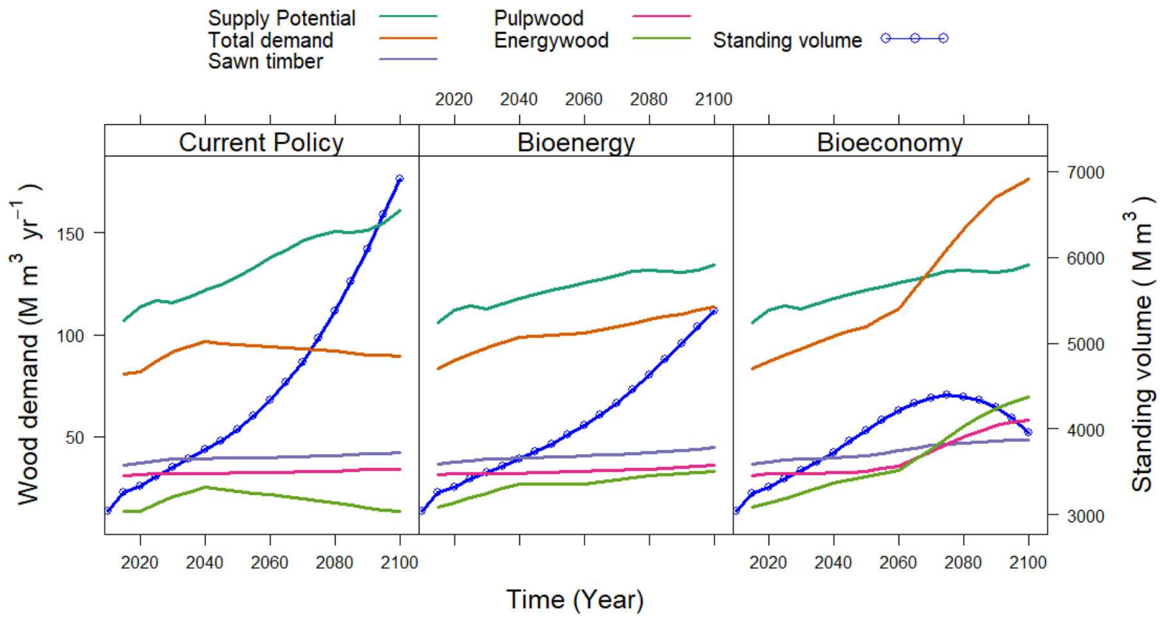

Figure 3. Global demand for industrial wood and different wood assortments (sawn timber, pulpwood and energywood) from Sweden (Million m^3 yr^{-1}) and the total standing volume (Million m^3) under the three demand scenarios: Current Policy, Bioenergy and Bioeconomy. The figure also shows the supply potential (Million m^3 yr^{-1}) of wood under each demand scenario.

m^3 ha^{-1}, resulting in a total volume increase from 16 million m^3 to 35 million m^3. In the production forest landscape, starting from the current level of around 8 m^3 ha^{-1}, deadwood density more than tripled (26 m^3 ha^{-1}) in the Current Policy, and more than doubled in the Bioenergy (to 21 m^3 ha^{-1}) and Bioeconomy (to 18 m^3 ha^{-1}) scenarios by 2100. In production forests, the density of deadwood increased by 2100 to levels (17–25 m^3 ha^{-1}) currently observed in set-asides. Consequently, the total amount of deadwood in the production landscape increased considerably in all scenarios.

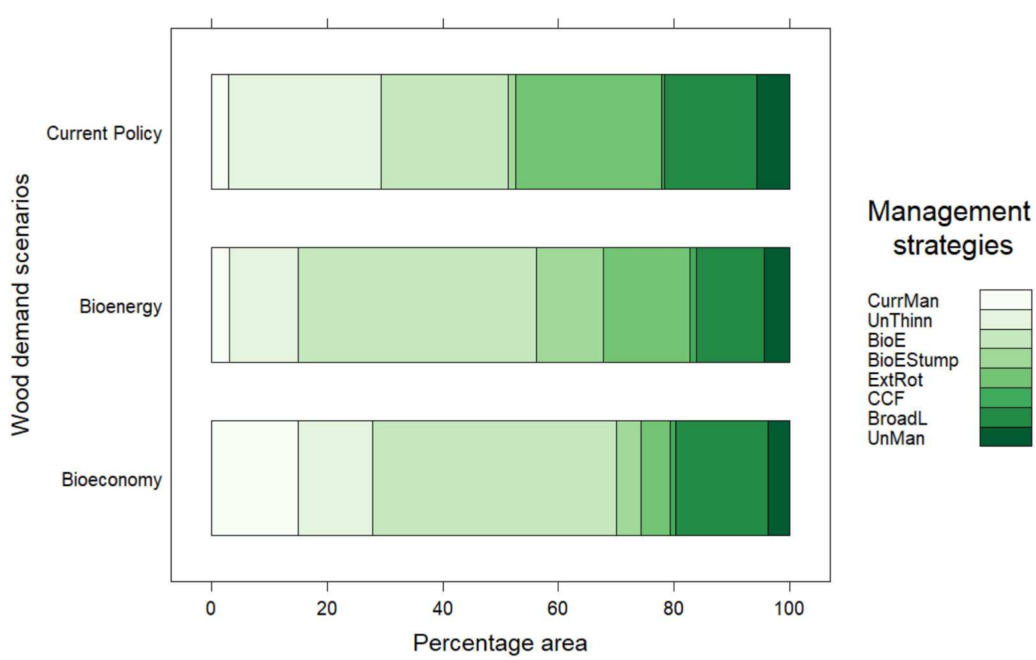

Figure 4. Percentage area covered by each management alternative under each wood demand scenario after optimizing for maximum Net Present Value (NPV). Management strategies were Current management (CurrMan), Unthinned management (UnThin), Bioenergy extraction (BioE), Bioenergy with stump extraction (BioEStump), Extending final felling (ExtRot), Continuous Cover Forestry (CCF), Promoting broadleaves (BroadL) and Unmanaged (UnMan).

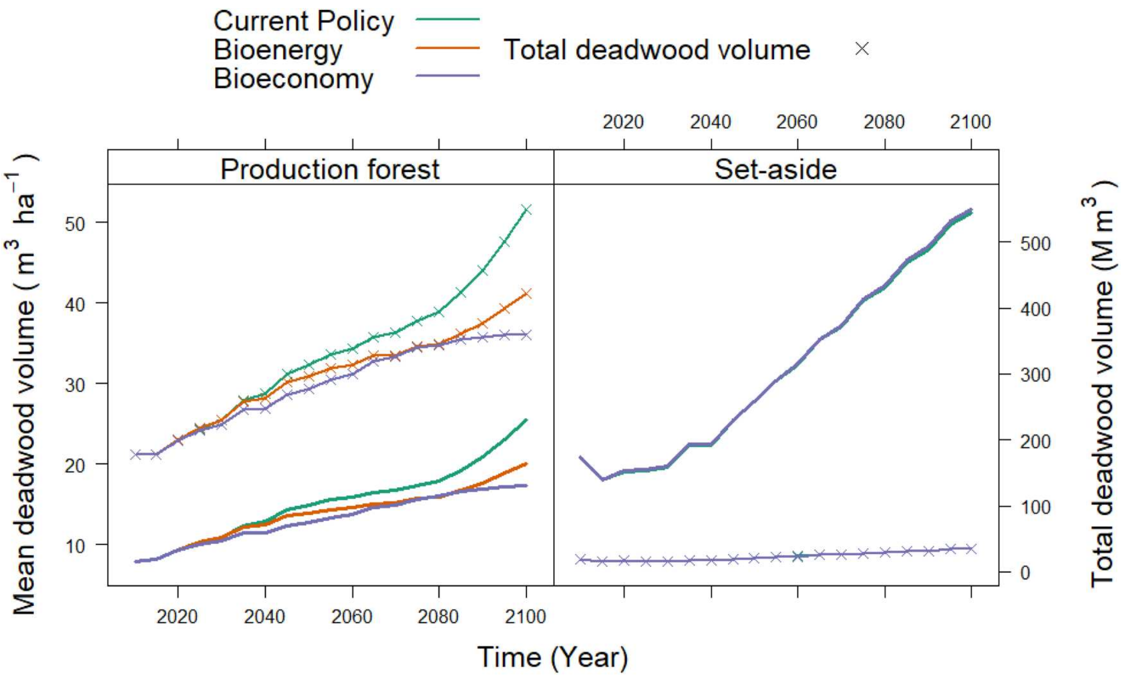

Figure 5. The volume of deadwood (m^3 ha^{-1}) and total dead-wood volume (Mm3) over time in set-asides and in areas used for timber production (productions forests) in Sweden under the three scenarios of wood demand: Current Policy, Bioenergy and Bioeconomy.

Area of old forest

The area of old forests on production land was projected to decrease dramatically from 2.1 million ha today to 0.5 under the Current Policy scenario, to 0.3 in the Bioenergy scenario and to 0.1 in the Bioeconomy scenario by 2100 (Figure 6). The percentage of old forests decreased from 9% during 2010 to 0.4–2.2% among the scenarios in 2100. In the set-asides, essentially all forest would be old in 2100; currently, 33% of the forests in set-asides are old.

Area of old forest rich in broadleaves

The percentage of old forest rich in broadleaves of the total forest area was 7.0% (1.6 Million ha) and 14% (0.2 Million ha) in 2010 in the forest area used for production and set-asides, respectively. In all scenarios, the percentage of old forest rich in broadleaves in production forests declined until 2040, after which it increased to current levels (Figure 7). In the Bioeconomy scenario the recovery was faster, but between 2060 and 2100 a further decrease was projected. These oscillations in area were highest in the Bioeconomy scenario and lowest in the Current Policy scenario. However, the area of old forest rich in broadleaves in set-asides increased by 5%, reaching approximately 0.15 Million ha by 2100.

Mean age of standing trees

The mean age of standing trees on wood production land changed from 57 years in 2010 to 42–58 years in the different scenarios (Figure 8). In set-asides, the mean age instead increased from 120 to 200 years.

Optimal combination of management strategies

In the Current Policy scenario, the dominant management strategies were intensive management such as Bioenergy extraction (BioE) and Unthinned (UnThin) management along with extensive management such as Extending the Rotation length (ExtRot; Figure 4). Relative to the Current Policy, the share of BioE increased further under the Bioenergy and Bioeconomy scenarios, and was applied almost on 40% of the area. Concomitantly, the share of UnThin and ExtRot decreased. Management to promote broadleaves (BroadL) was an important management alternative in all scenarios (10–15%). Continuous Cover Forestry (CCF) and even Unmanaged (UnMan) were least applied in all scenarios. CCF was chosen on only 0.5–1% of the area in the three scenarios. The UnMan alternative was implemented on 2%, 0.8% and 0.1% of the landscape in the Current Policy, Bioenergy and Bioeconomy scenarios, respectively. In addition, the 3.6% of the landscape which is legally set-aside was fixed to be unmanaged in the simulations.

Discussion

Our work suggests that the global demand for Swedish wood will increase in the future, especially under a Bioeconomy scenario. Meeting this demand will

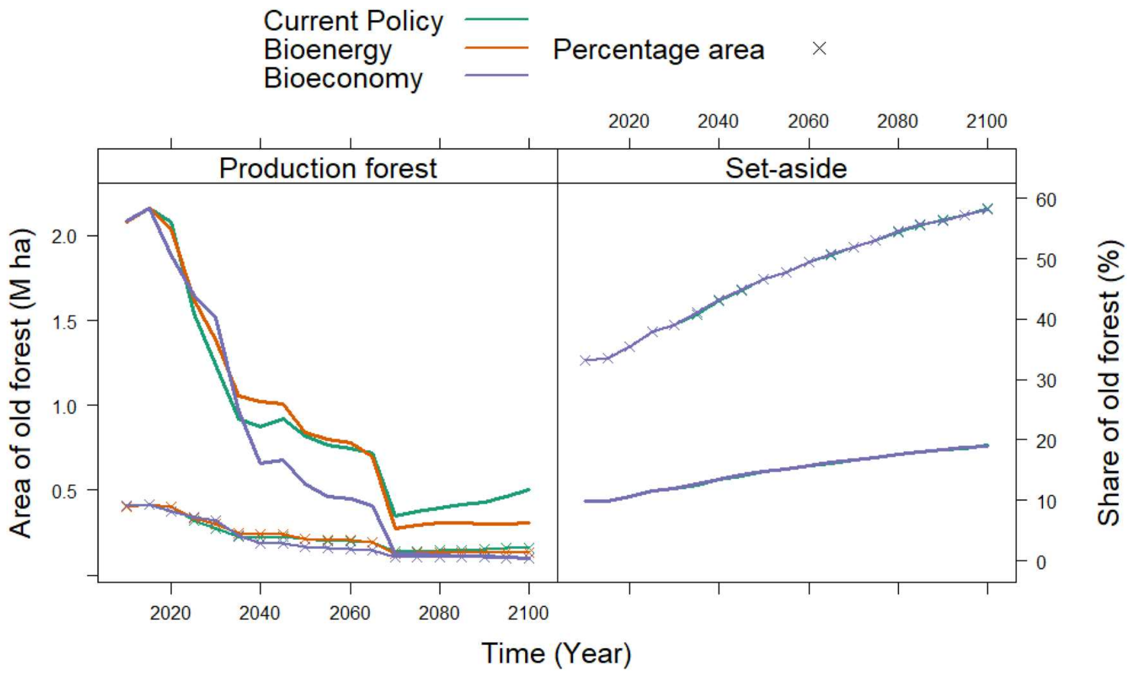

Figure 6. Area (Million ha) and the share of old forests (% of total area) in set-aside areas and production forests. Forest with stand age ≥140 years in northern Sweden and ≥120 years in southern Sweden were considered old.

require more intensive forest management on a larger proportion of forest land than currently practiced. This intensive management will decrease the area of old forests, old forests rich in broadleaves and the mean age of standing trees. However, the deadwood volumes are still projected to increase.

Wood supply from Sweden, challenges and opportunities

Even with intensive forest management, the demand for energywood in the Bioeconomy scenario cannot be fully satisfied. Consequently, sawn timber and pulpwood

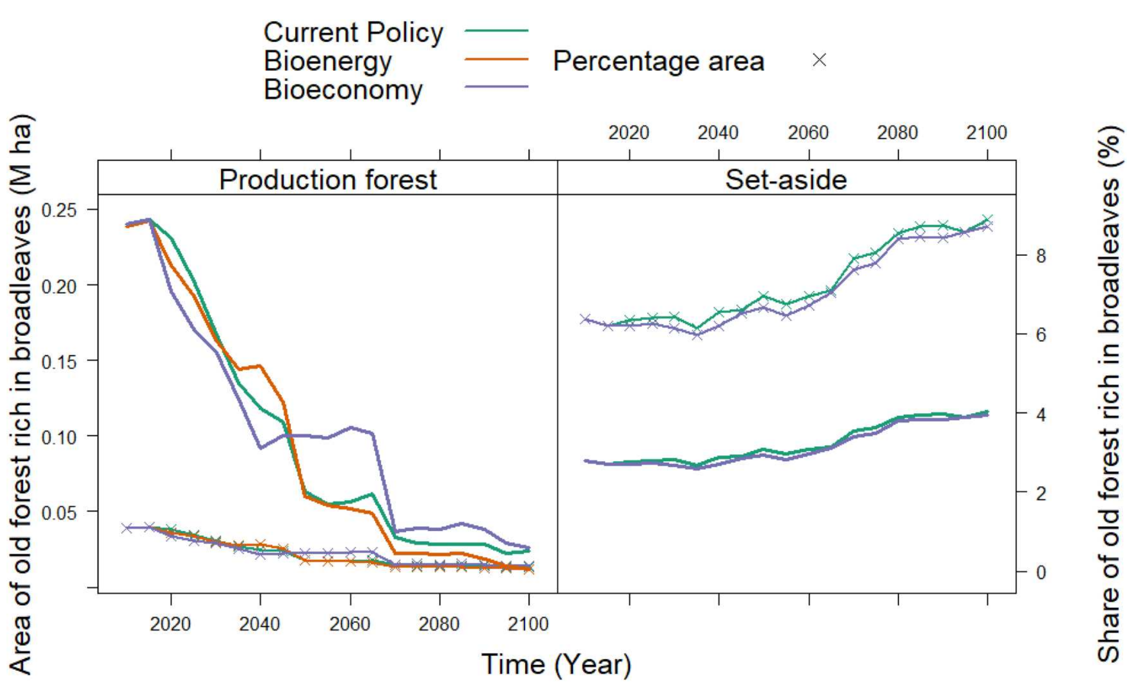

Figure 7. Area (Million ha) and the share of old forest rich in broadleaves (% of total area) in set-asides and production forests. Forest stands with a minimum proportion of 25% of broadleaves with age ≥ 80 years in northern Sweden and ≥ 60 years in southern Sweden were considered as old forest rich in broadleaves.

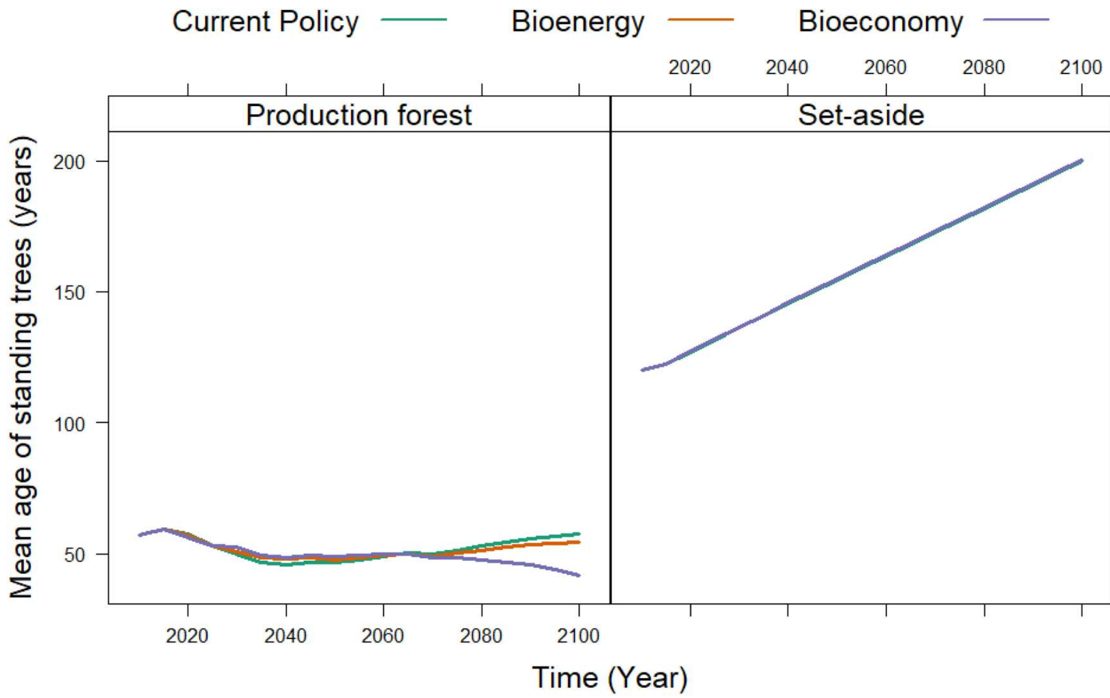

Figure 8. Mean age of standing trees in set-asides and production forests Sweden under the three wood demand scenarios: Current Policy, Bioenergy and Bioeconomy.

were burnt to meet the projected wood demand. Harvesting such volumes will mean unenduring forestry and will not be possible in the long term. The bioeconomy scenario is compounded by the fact that ambitious climate mitigation policies may result in significantly higher future demand for energywood. For example, Nordström et al. (2016) projected a doubling of energywood by the end of the century in a "high biomass demand" scenario. Moreover, a scenario with 2% yearly increase of the Swedish forest industry to partly meet the projected increasing energy demand could mean harvesting more than 150 Mm^3 yr^{-1} (Skogsutredningen 2020). However, the ownership structure and policy recommendations in Swedish forestry may also limit the actual harvesting of the potential supply, particularly since around half of the Swedish forest are privately owned (Nordström et al. 2016). Some landowners prioritize other objectives over the income from wood (Eggers et al. 2014). Environmental concerns have also restricted the extraction of whole stumps after clear-felling in Sweden, further reducing the potential harvest levels (Johansson and Ranius 2019).

Impacts on the biodiversity indicators

We show that the area of old forests will almost disappear on wood production land by 2060 in the Bioeconomy scenario. Even in the Current Policy scenario, the wood demand increased until 2040, driving a continued decline of old forests. This is due to clear-felling at much earlier age than the applied threshold and natural longevity (Kuuluvainen and Gauthier 2018). While the decline of old forests may level off when the wood demand stabilizes after 2040 in the Current Policy scenario, the remaining forest will be younger than the threshold set by the Swedish Environmental Objectives system. Our quantitative work linking global-/EU- and national-level forest management and dynamics thus confirms the qualitative prospects by Bergeron et al. (2017) and Kuuluvainen and Gauthier (2018) that under current harvest levels, old forests will continue to decline. In the Bioeconomy scenario, we even project that the decline will be completed by around 2070, leaving essentially no old forest in the wood production land. In contrast, the Canadian and Russian boreal forests have preserved their structural and biological diversity, mainly due to their limited accessibility (Aksenov et al. 1999; Mackey et al. 2015). However, increased harvesting rates and frequent and more intense fires are projected to lead to a decline in old forest there as well (Aksenov et al. 1999; Bergeron et al. 2017). On the other hand, burned old forests retained large quantities of old forest structures and are crucial for fire-dependent biodiversity.

Our conservative assumptions may have underestimated the intensity of the future forest management needs. Recently Skogsstyrelsen (2019) updated the area of legally protected national parks and nature reserves from 3.6% (Eriksson et al. 2015a) that we assumed to 6%, with an additional 6% designated as voluntary set-asides. This exceeds the 0.1–2% of unmanaged forest in our simulations. More extensive set-asides may occur in the future. Considering the current age structure, the loss of old forest due to heavy harvests on wood production land cannot be compensated, particularly in a Bioeconomy scenario. The EU biodiversity strategy for 2030 (European Commission 2020) targets for a coherent protected area network covering 30% of land (including 10% strictly protected and 20% with management for conservation). However, the selection and management of this 20% area is unclear and may include unproductive forest excluded in our study. Our findings indicate that Sweden faces challenges in meeting the EU biodiversity targets for 2030, especially in a Bioeconomy scenario. Therefore, finding a solution to satisfy growing wood demand while increasing forest conservation area remains unresolved.

The stabilization of wood demand after 2050 likely explains the increase in old forest rich in broadleaves in the Current Policy and Bioenergy scenarios. However, in the Bioeconomy scenario, this area initially decreased until 2040, then increased until 2060 before subsiding. This was due to the use of surplus conifer pulpwood and sawn timber as energywood to meet the rising energywood demand (Figure A1). By 2100, a quarter of the energywood came from pulpwood or sawn timber. Forestry optimization prioritized harvesting of conifer over broadleaved trees due to higher profitability. Consequently, surplus conifer pulpwood and sawn timber were used as energywood, resulting in an increase in old forest rich in broadleaves. This increased contribution of energywood from other sources possibly caused the expansion of old forest rich in broadleaves by 2050 (Figure A1). However, it remains uncertain if the harvesting and use of conifer timber over broadleaves for energywood will occur. If not, the area of old forests rich in broadleaves should decrease by the end of the century in these scenarios. Nonetheless, the wood demand significantly increased in the Bioeconomy scenario by 2060, resulting in higher harvest levels and a reduction in the area of old forest rich in broadleaves by 2060 onwards.

The deadwood volume is projected to increase more than two folds and three folds on production and set-aside land, respectively, in all scenarios. Several studies have shown that climate change enhances deadwood formation in the forest (Kellomäki et al. 2008; Mazziotta et al. 2014). Soil mineralization increases with temperature, rising site fertility, as long as the site is not affected by droughts (Hartmann 2011). Thus, climate change leads to early growth culmination and enhanced life cycle process in trees, resulting in increased deadwood production. Set-aside areas, without harvesting may contribute to higher volume growth and stand density, potentially causing more deadwood formation compared to production land. Our results align with Alrahahleh et al. (2017) projecting a 146% and 57% increase in deadwood volume in northern and southern Finland, respectively. Eggers et al. (2020) also predicted increased deadwood accumulation in Swedish production and set-aside forests. Another reason for high deadwood volume in the Current Policy scenario on production land may be the absence of thinnings (UnThinn) and postponing final felling (ExtRot) leading to high natural mortality and subsequent deadwood formation due to accumulating growing stock (Elfving 2010; Subramanian et al. 2016).

The choice of different management strategies

Different management strategies were selected based on the total wood demand and demand for each specific wood assortment for each scenario. Intensive management strategies like BioE and UnThin were dominant in the Current Policy scenario along with extensive management ExtRot, despite not having high wood demand. This was because energywood was obtained only from logging residues and wood that did not meet size requirements for sawn timber and pulpwood. Logging residues were extracted only in intensive management strategies, like BioE and BioEStump. In the UnThinn management alternative, there may be a high proportion of small trees that do not meet size requirements for sawn timber and pulpwood at final felling, and therefore can only be used as energywood.

Postponed final felling was selected in many stands in the Current Policy scenario due to increased growth rate resulting from climate change and reduced wood demand. This explains the dominance of the ExtRot management alternative in this scenario. During the beginning of the simulation, the annual wood demand predicted by the GLOBIOM model in all wood demand scenarios was lower (76 Million m^3) than the current harvest level in Sweden, which stands at around 90 Million m^3 (SLU 2020). The climate scenario used in the Current Policy scenario is RCP8.5, which projects the highest tree growth.

In the Bioenergy scenario, due to high energywood demand, more logging residues were extracted compared to the Current Policy scenario. This resulted in a larger managed area under BioE and BioEStump in the Bioenergy scenario, where slash being harvested in the former and both slash and stumps in the latter. Harvesting stumps is more expensive than harvesting slash (de

Jong et al. 2017), which is why the Heureka model prioritize harvesting slash over stumps. Additionally, in both the Current Policy and Bioenergy scenarios, the stump and slash harvest were limited to 30% and 80% of the annual final felled area, respectively, due to environmental concerns (de Jong et al. 2017). This restriction curtailed the implementation of BioEStump management. This may account for the dominance of BioE management in the Bioenergy scenario. Surplus sawn timber and pulpwood were allowed to be used as energywood since its demand was very high in the Bioeconomy scenario. Since stump extraction is more expensive than harvesting extra timber and pulpwood, and the goal function was to maximize NPV, this led to lower proportion of intensive management strategies such as BioE and BioEStump in the Bioeconomy scenario than the Bioenergy scenario.

CCF (Continuous Cover Forestry) is the least implemented management alternative in all scenarios due to its relatively poor economic performance in the Heureka model. However, other Scandinavian studies (Peura et al. 2018; Eggers et al. 2020) suggest that CCF can be more profitable than clearcut forestry. Eggers et al. (2020) applied CCF in only 65% of the study area, allowing increased production from the remaining area with clearcut management. Peura et al. (2018) used Pukkala et al.'s (2013) growth model for CCF simulation. Parkatti et al. (2019) argued that Pukkala et al.'s (2013) model predicts unrealistically high ingrowth, shorter harvesting intervals and higher yields. These could be the reasons for higher economic profitability in CCF in those studies. CCF also enhances multi-functionality in the forest, including its carbon sequestration capacity (Pukkala 2016; Peura et al. 2018). But these studies did not consider the substitution effect of harvested timber biomass which is important for calculating the carbon sequestration capacity in a forest (Lundmark et al. 2018). Eyvindson et al. (2021) found that CCF can be more profitable than clearcut forestry, due to increased log extraction from CCF managed forests as the largest trees are harvested during thinning and also less expenses since the forests are naturally regenerated. However, higher harvesting operation costs reduce the overall profitability in a CCF managed forest.

Challenges associated with climate change

The Heureka system is a versatile tool for simulating the impacts of forest management on structure and economic outcomes. To incorporate climate change, an approximation model is implemented in Heureka based on the process-based model BIOMASS (McMurtrie and Wolf 1983; Eriksson et al. 2015b). The approximation model estimates the effect of climate on tree growth by comparing growth from 2071 to 2100 to that from 1971 to 2000. This change in growth is then applied to modify relationships within Heureka, such as tree size, age, site index, vegetation type index and temperature sum (Eriksson et al. 2015b; Heureka Wiki contributors 2016). Notably, the site index plays a crucial role in representing climate sensitivity in Heureka. As temperature rise, the model assumes a higher site index, resulting in faster tree growth. However, this approach has limitations in capturing extreme climatic events like droughts and early summer frosts. Heureka thus does not include all the variations in future climate, as only a 30-year average period (2071–2100 in comparison to 1971–2000) is used, thus it may overestimate the future growth (Subramanian et al. 2019). Therefore, the future potential wood supply from Sweden may be overestimated in this study. There are several other factors which can influence the growth and development of forest under a changing climate that we have not considered in this study. For example, biotic damages like pest and pathogen infestation, abiotic damage like storms and wildfires, can affect the growth and development of forest landscapes to a greater extent than they do at present. The alternative management strategies we recommend in this study may not be effective against these risk factors. Therefore, before implementing alternative management strategies the associated uncertainties should be considered carefully. Supplementary Material S2 provides a concise presentation of sensitivity of stand volume growth under different climate scenarios.

Climate change mitigation potential by substitution effects of wood products

We have not conducted a full life-cycle assessment of wood products in this study. To fully understand the mitigation potential of forest ecosystems, it is important to consider both the dynamics of the growing stock in the forest and the substitution effects of harvested wood products (Lundmark et al. 2018; Niemi et al. 2025). When estimating substitution effects, it is crucial to account for avoided emissions due to the replacement of fossil fuels with renewable forest-based products. Mitigation potential will be higher when harvested wood is directed to uses that substitute fossil-intensive materials and have a long lifetime, such as construction materials, and increasing energy recovery and avoiding emitting carbon at the end of life of harvested wood products by carbon capture and storage (Niemi et al. 2025). As illustrated in our Bioeconomy scenario, burning saw logs and pulpwood for energy can result in increased net emissions. However, given the high energy demand in the Bioeconomy scenario, not using woody biomass for energy may lead to a greater reliance on fossil fuels.

On the other hand, in terms of supply and demand, when the demand for a particular commodity increases, its price typically rises, allowing forest owners to gain more profit by selling the commodity at a higher price. In our study, particularly in the Bioeconomy scenario, the demand for wood and all wood assortments is increasing (Figure 3). The demand for energywood grows significantly after 2060 in this scenario. As a result, forest owners can earn more by selling trees as energywood because the rotation age can be shorter, providing quicker income. Moreover, the quality of wood does not affect the price for energywood, meaning that production costs can be lower with fewer interventions.

Conclusions

We show that the global demand for wood from Sweden is projected to increase in the future in all wood demand scenarios. The wood demand of the Bioeconomy scenario even surpasses the sustainable supply of Swedish forest by 2070. Intensive management strategies may be necessary if we want to meet the increasing future demand from Sweden. This will mean that the old forest and old forest rich in broadleaves will disappear from the production landscape and will only be found in set-aside areas. However, the deadwood volume will continue to increase due to currently young forests and climate change. The dominant management alternative will change from current management which include a Pre Commercial Thinning, two to three thinnings followed by clear cutting for current policies into even-aged management with bioenergy extraction if the demand will follow Bioenergy or Bioeconomy scenarios.

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