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Can extended rotations promote the reconciliation of multiple management goals set for production forests in Nordic countries?

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ABSTRACT

We studied the ability of extended rotations as a measure to promote sustainable management of production forests in Nordic countries. We carried out scenario analyses for three large forest regions in Southern Finland, Central Sweden, and South-Eastern Norway, where forestry has a high socioeconomic value. We analyzed the effects on wood production, carbon sequestration, and the amount of produced deadwood over the 50 years. In the reference scenario (BAU), the prevailing management of production forests was applied. In the scenario for extended rotations (EXT), rotation lengths were extended by 30 years, on average. We used data from national forest inventories to represent the current stage of the regions' forests and produced future forecasts using local models, which have been widely applied in large-scale analyses. The increase in carbon sequestration and production of deadwood in production forests can be achieved by lengthening rotations but only at the expense of harvesting removals. The increase in annual carbon sequestration is between 0.7 and 1.6 Mg CO_2 eq ha^{-1}. Natural mortality increases by 20–30% along with the amount of deadwood by 0.15 m^3 ha^{-1} a^{-1}, on average. The decrease in the mean annual harvesting removals varies from 0.4 to 1.6 m^3 ha^{-1} a^{-1} from region to region.

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Forest management scenario; wood production; forest carbon storage; deadwood production

Introduction

The most abundant forest resources in Europe are located in the boreal forest zone of Nordic countries. Those countries are among the key forestry countries in Europe (Forest Europe 2020). The majority of Nordic forest area (ca. 80%) is available for wood production. Therefore, sustainable use of production forests is crucial for meeting the sustainable development goals in Nordic countries. Forestry has negative and positive effects on sustainability (Baumgartner 2019). Sustainable use of forests is about finding a balance between different and often contradicting goals (Blattert et al. 2023). The most urgent challenge in sustainable forest management is to find feasible measures, which secure the vitality and resilience of production forests and are capable of reconciling different management goals under increasingly challenging growing conditions caused by climate change.

Prevailing management guidelines for production forests include actions and practices aiming at maintaining vitality and safeguarding forest biodiversity (Rantala 2011; Lindahl et al. 2017). However, there is still an ongoing need to further improve management practices to strengthen resilience and prevent biodiversity loss (Gauthier et al. 2015; Alrahahleh et al. 2017), which is a major threat to the ecological sustainability.

The high carbon sequestration rate of massive Nordic forest resources is important in the mitigation of climate change. Despite intensive harvesting of industrial wood, the volume and biomass of the growing stock in Nordic forests have steadily increased over the past decades. The growth rate of production forests has increased partly due to the forest management practices for wood production including a shift from selective cuttings to intensive rotation forestry, and partly due to the warmer climate (Elfving and Tegnhammar 1996; Henttonen et al. 2017). In recent years, however, forest growth has turned to a slight decline in both Finland and Sweden (Hannertz and Ekström 2023; Henttonen et al. 2024). At the same time, the demand for industrial wood is increasing. Therefore, the increase in carbon storage of growing stock is likely to slow down noticeably. Blattert et al. (2023) have recently concluded that Finland and Sweden cannot fulfil the increased harvest demands linked to the ambitious 1.5°C global warming level target. They also stated that the goals mentioned above are contradicting and cannot be met without compromises (Blattert et al. 2023).

Maintaining sustainable wood supply from production forests is highly important for the socio-economy, especially in Finland and Sweden. Abundant forest resources, modern

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forest industry, as well as advanced forest management and wood procurement, enable efficient supply of forest biomass. Most of the forest area under wood production in Nordic countries is managed according to the principles of rotation forestry, which has been recognized to be an efficient management system from the viewpoint of wood production (Rautio et al. 2024).

Extended rotations in production forests have been proposed to be a viable option to reconcile different management goals. Longer rotations contribute positively to biodiversity values by increasing natural mortality resulting in a larger amount of deadwood and increasing the size of retention trees in final fellings (Koskela et al. 2007; Felton et al. 2017). The amount and quality of deadwood are important structural characteristics of forest biodiversity. Especially large-size deadwood and deadwood of broadleaved tree species are valuable. Unfortunately, they are also very sparse in managed coniferous forests. The amount of deadwood can be increased, e.g. by saving dead trees during harvesting, favouring broadleaved tree species throughout the rotation, and extending rotations (Koskela et al. 2007; Felton et al. 2017).

The ability of a forest to sequester carbon is affected by the existing carbon storage in forest soil and in living and dead forest biomass and by the capacity of the forest ecosystem to uptake carbon from the atmosphere. Forest soil is the largest storage of forest carbon. In Northern Europe ca. 60% of carbon is in soil (Liski et al. 1998). In production forests, both carbon storage and uptake of carbon can be regulated with the help of forest management practices. In prevailing even-aged forest management final fellings are often carried out well before the biological maturity of forest stands. Long rotations have been suggested to have beneficial climate impacts due to increased carbon storage (Kaipainen et al. 2004; Liski et al. 2011; Zanchi et al. 2014; Ekholm 2016; Pingoud et al. 2018) and they might increase forests' climate benefits (Lundmark et al. 2018).

A comprehensive assessment of extended rotations' impacts is needed to support decisions in forest management planning and forest policy making. Although the effects of extended rotations occur at the stand level, this information needs to be upscaled and analysed at regional levels for decision-making. The general objective of this study was to assess the impacts of extended rotation in large forest regions in Finland, Norway, and Sweden, where commercial wood production plays a crucial role. More specifically, we analysed the effects of extended rotations on wood production, above- and below-ground carbon storage of living trees, and the produced deadwood volumes over the 50 years. We also studied trade-offs between wood production and carbon sequestration of living trees as well as between wood production and deadwood production. We constructed alternative long-term management scenarios for a large forest region in each country using uniform assumptions and forest management strategies for the assessment. Forest development forecasts were calculated separately for each region using local models and software.

Material and methods

Study approach

We constructed two alternative management scenarios for assessing the long-term impacts of forest management strategies in three large forest regions in Southern Finland, Central Sweden, and South-Eastern Norway. We used the most recent measurement data from national forest inventories (NFI) to provide a representative description of the current state of regions' forests. We produced forecasts of the forest development applying similar management strategies in all countries but using tailored site- and tree-species-specific management guidelines separately for each country. By doing so, we wanted to ensure the compatibility and feasibility of scenarios in the local operating environment of forestry in each country. The time of the management scenarios was 50 years. The effect of climate change was not included in the analysis because of the lack of such reliable forecast methods, which can predict both the positive (e.g. increased growth rates of forests) and the negative effects (increase of biotic and abiotic damage) on forest development affected by changing climate. In the analysis on forest carbon sequestration, we restricted to carbon sequestration of living trees, because there are no established methods to predict the development of forest soil carbon stocks in forest management scenarios.

To obtain reliable predictions of forest resources for each region, we calculated forecasts using local simulation tools, which are tested and widely applied in large-scale analyses. We chose Motti for Finland (Hynynen et al. 2015), Heureka Regwise for Sweden (Lämås et al. 2023), and SITree for Norway (Antón-Fernández and Astrup 2022). Each of these simulation tools is equipped with local growth and yield models which have been developed and validated using extensive empirical data from each country (e.g. Fahlvik et al. 2014; Hynynen et al. 2014). Further, a cross-validation has been carried out for models of Motti and Heureka by Aldea et al. (2023).

Mortality models based on the data from production forest stands may result in seriously biased predictions when applied to unmanaged stands (Hynynen et al. 2002). To improve the prediction of natural mortality for all kinds of forests (i.e. both production and protected forests), Siipilehto et al. (2020) reported a set of mortality models applying pooled data from Finland, Sweden, and Norway in fitting and validating the models. Due to the good performance of these models in each country, they were assessed to be the best available ones to be applied in our analysis. Therefore, each of the local simulation tools used in our analysis (Motti, Heureka, and SITree) was equipped with the mortality models of Siipilehto et al. (2020).

Scenarios

Business as usual (BAU)

The basic scenario titled Business as Usual (**BAU**) served as a reference management scenario, in which the intensity of forest management was defined to the level, which is currently prevailing in each region. The annual areas of silvicultural treatments and harvesting removals were obtained from forest statistics for Finland and Sweden. For Norway, we used a probability model fitted to the Norwegian NFI data to select the plots, in which thinning or final felling will be carried out. This procedure was used to depict management patterns currently seen in Norway. In the BAU scenario for Finland and Sweden, the timing and intensity of forest management practices were based on the local silvicultural guidelines and prevailing forestry practices by country. Therefore, rotation lengths in production forests can be considered country-wise "business as usual".

Extended rotations (EXT)

In the scenario for extended rotations (**EXT**) forest management was similar to BAU except for the applied rotation lengths. In the EXT scenario, rotation was, on average, 30 years longer than that of the BAU scenario. For Finland and Sweden, no more than three commercial thinnings were allowed during the rotation. For Norway, the maximum number of commercial thinnings was restricted to two.

Data

Management scenarios were constructed for three large forest regions in Southern Finland, Central Sweden and South-Eastern Norway, where forestry has a considerable socio-economic impact (Figure 1, Table 1). The total area of production forests of these selected regions was 14.1 million hectares and the total volume of the growing stock was 1 970 million cubic meters (Table 1).

In Southern Finland, the analyzed region covers five counties, Kanta-Häme, Päijät-Häme, Pirkanmaa, Etelä-Savo, and Keski-Suomi (Figure 1). The total area of production forests is 4.2 million hectares. Annual removal of the study region accounts for 34% of the total annual harvested volume in Finland. Data representing the region's forest resources consist of 12 062 systematically located sample plots of the 12th NFI (NFI12, 2014–2018). The data cover all forestry land in the region (Korhonen et al. 2021), including production forests as well as protected forests and the forests under restricted forestry use. Each sample plot represents ca. 334–387 ha of forest land. The data form a representative sample of the region's forests including various site-fertility classes, from the most fertile to barren sites on mineral soils and drained peatlands. Dominant tree species are Scots pine (*Pinus sylvestris* L.) (47%), Norway spruce (*Picea abies* (L.) Karst) (39%), and birch species (silver birch, *Betula pendula* Roth., on mineral soils, and downy birch, *Betula pubescens* Ehrh., on drained peatlands) (12%). A detailed description of NFI12 measurements and collected data can be found in the reference (Korhonen et al. 2021).

In Central Sweden, the analyzed region covers three counties, Västernorrland, Jämtland, and Gävleborg (Figure 1). The total area of production forests is 5.8 million hectares. Annual removals of the study region account for 23% of the total harvested volume in Sweden. We used the data from the NFI measurements conducted during 2008–2012. The NFI data in this region consist of a systematic network of 6 626 circular sample plots in clusters spread across the region (Jonas et al. 2014). Each sample plot has a unique plot ID and has an area of 0.0314 ha, corresponding to a radius of 10 m. The dominant tree species are Norway spruce (44%) and Scots pine (37%), followed by birch species (12%). The site index (base age 100 years) in the region ranges from SI 10 m to SI 30 m.

In South-Eastern Norway, the analyzed region includes productive forests (annual increment greater than 1 m^3 ha^{-1}) from Viken, Innlandet, Vestfold og Telemark, and Rogaland counties (Figure 1). The total area of production forests is 4.1 million hectares. Annual removals of the study region account for 75% of the total harvested volume in Norway. We used 4 683 plots from the Norwegian 2014–2019 NFI (Breidenbach et al. 2020) data to represent the region's forest resources. The plots are circular with an area of 250 m^2. The plots are placed in a 3×3 km grid and each plot represents approximately 900 ha. In the productive forest area included in this study, 47% is dominated by Norway spruce, 36% by Scots pine, and 17% by birch. The site index in the region (base age 40 years) ranges from SI 6 m to SI 26 m. The most common site indices are SI 8 m (26% of the area) and SI 11 m (22%), while SI 23 m (2%) and SI 26 m (0.1%) are the least represented ones.

The three regions differ from each other in the forest development-class structure (Figure 2). In the Finnish region, 68% of the forest area is covered with young or advanced thinning stands. Forests in the Swedish region are, on average, even younger than in the Finnish region. The proportion of thinning stands is smaller (ca. 40%), and the share of young stands is greater (17%) than in the Finnish region. In the Norwegian region, almost 60% of productive forests are either advanced thinning stands or mature forests. These structural differences affect the amount and timing of different types of treatments, as well as mortality rates and carbon storage changes during the 50 years.

Forecasting methods

In the analysis for the Finnish region, we used a simulation-optimization method, which has been applied in recent regional and national forest management scenario analyses (e.g. Hynynen et al. 2015; Haikarainen et al. 2021). First, we constructed a set of alternative management regimes tailored for different types of forest stands. The goal was to include all the management options, which agree with the management principles of different scenarios. No management practices were simulated for protected and other set-aside forest areas.

Second, we simulated alternative developments for each NFI sample-plot stand according to all pre-defined management regimes. We used Motti software, which includes a large set of models to predict the natural dynamics as well as the effects of silvicultural treatments (Hynynen et al. 2002, 2014, 2015; Repola et al. 2018; Siipilehto and Mehtätalo 2013). The technical design of Motti is described by Salminen et al. (2005).

After the simulations, we used linear programming to introduce scenario-specific constraints into the analysis. For the BAU scenario, we restricted annual harvested volumes and the areas of silvicultural practices to the level reported in forest statistics (Official Statistics of Finland 2023b). For

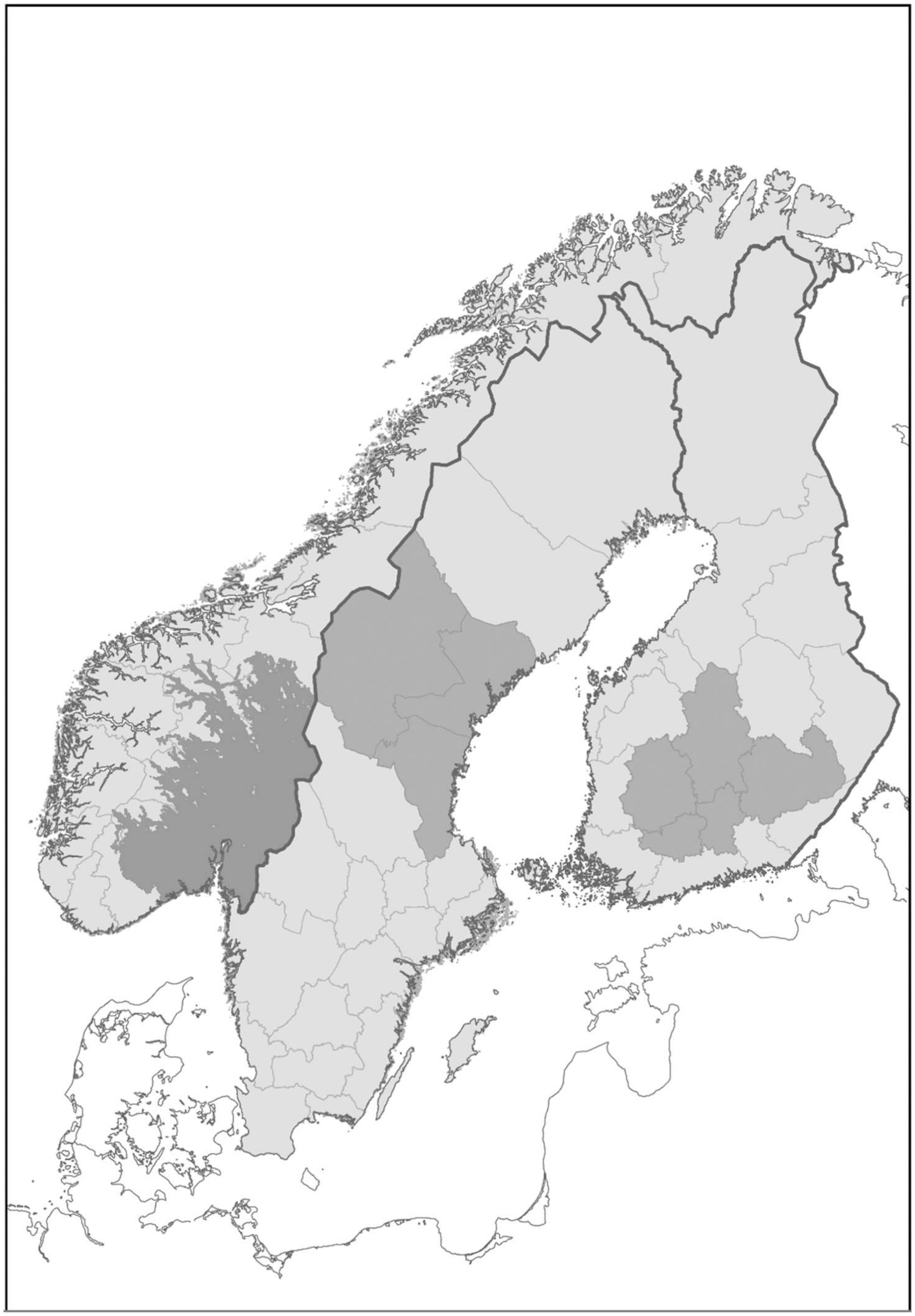

Figure 1. Forest regions of the scenario analyses in Southern Finland, Central Sweden, and South-Eastern Norway.

the EXT scenario, we constrained rotation periods to be longer than those in the BAU scenario to achieve the required extension to rotation periods. We applied linear programming software J (Lappi and Lempinen 2014) to select one scenario-specific management regime for each stand. The selection procedure is described in detail by Huuskonen et al. (2020).

In the analysis of the Swedish region, we applied the Heureka model, which is a widely used Decision Support System software developed by the Swedish University of Agricultural Sciences (Lämås et al. 2023). The landscape simulating tool, Heureka-Regwise (version 2.16.4.0) was used in this study. Heureka's growth simulator consists of a set of empirical growth and yield models that simulate tree growth, including separate models for stand establishment, ingrowth, mortality, diameter and height increment (Fahlvik et al. 2014). All these models were developed using regression analysis and fitted to the data from the NFI. The growth simulator allows users to generate various forest management alternatives for each treatment unit. These management alternatives differ in the type of management system and/or timing of the silvicultural practices implemented for each treatment unit. Forest management systems like even-aged, uneven-aged, and unmanaged can be simulated along with the set of silvicultural rules like soil scarification, type of regeneration, thinning, final felling, fertilization, etc.

Table 1. Information on the forests of study regions in Southern Finland, Central Sweden, and South-Eastern Norway based on National Forest Inventories (NFI).

	Finnish region	Swedish region	Norwegian region
	NFI12[a]: 2014–2018	NFI[b]: 2008–2012	NFI[c]: 2014–2018
Forest land area, total, mill. Ha	4.4	6.9	4.2
Forest area under wood production, mill. ha	4.2	5.8	4.1
In production forests			
Growing stock, total, mill m^3	645.0	756.5	568.0
Mean volume of the growing stock, m^3 ha^{-1}	151.2	132.6	140.5
Annual harvesting removals, total, mill m^3	24.4	21.9	9.3
Harvesting removals, per ha, m^3 ha^{-1} a^{-1}	5.7	4.0	2.2
Amount of deadwood, m^3 ha^{-1}	4.8	6.6	10.7
Total biomass of living trees[d], mill t.	437.0	596.6	443.9
Mean biomass of living trees, t ha^{-1}	102.4	104.0	109.8
Total carbon storage of living trees, mill t CO_2eq	801.2	1093.7	813.8
Mean carbon storage of living trees, t CO_2 eq ha^{-1}	191.4	190.8	201.3

[a]Official Statistics of Finland (2023a).
[b]Official Statistics of Sweden (2023).
[c]Statistics Norway (2023).
[d]Total biomass of living trees includes biomasses of stem, branches, coarse roots, and fine roots.

NFI sample-plot data were used as input for Swedish simulations. The management actions in the BAU scenario were set according to the prevailing practices in the respective counties. The timing of management actions like cleaning, thinning, and final felling as well as species regenerated, and regeneration methods were obtained from the recent Swedish Nationwide Forestry Scenario analysis report (Eriksson et al. 2015). Rotations were extended by 30 years in the EXT scenario by adjusting the "Minimum relative age of final felling" parameter in Heureka Regwise so that the mean final-felling age of the forest stands was increased by 30 years. All other model parameters remain the same for the BAU and EXT scenarios. Forest management alternatives were applied to forests available for wood production.

In the analysis of Norwegian region, we used the single tree simulator framework SiTree (Antón-Fernández and Astrup 2022) with the following custom-built functions: Diameter growth was calculated using models of Bollandsås and Næsset (2009), height growth was estimated using longitudinal height-diameter curves based on shape constraint additive regression models fitted to the Norwegian NFI (similar to Schmidt et al. 2018), mortality using Siipilehto et al. (2020), recruitment with imputation using NFI data from 2004 to 2018, and management using final felling and thinning equations from Antón-Fernández and Astrup (2012). The simulations took the NFI data as a starting point. Both BAU and EXT scenarios use the same models and parameters for SiTree and use the final felling logistic regression model from Antón-Fernández and Astrup (2012) stochastically to select the stands to be harvested. However, in the BAU scenario the final-felling model was used directly, while in the EXT scenario only stands that have reached maturity age were allowed to be harvested. Neither management scenario included forest fertilization or deployment of improved forest reproductive material in forest regeneration.

Results

Forest management intensity in the regions

In general, there are noticeable differences in the intensity of forest management between the three regions. In the Finnish, Swedish and Norwegian regions, the annual area of commercial harvesting (i.e. thinnings and final fellings) in the BAU scenario covers 3.2%, 2.3%, and 0.9% of the total area of production forests, respectively. Thinning area covers 58% of the total harvesting area in the Finnish region and 64% in the Swedish region. In the Norwegian region, most of the harvestings are final fellings, the proportion of thinnings being 20% of the total annual harvesting area.

Effects on forest management and wood production

Harvesting area

Extended rotations result in a considerable decrease in the annual final-felling area in each region, as expected (Figure 3). During the 50-year study period, an annual final-felling area in the EXT scenario decreases by ca. 50%, 35%, and 26%, in the Finnish, Swedish, and Norwegian regions, respectively. The greatest effect can be seen in the first half of the 50-year scenario period, especially in the Finnish and Norwegian regions. The difference between the scenarios BAU and EXT decreases towards the end of the period in all the regions.

In the Finnish and Norwegian regions, extended rotation increases the area of commercial thinnings. In the Finnish region, the increase in thinning area is 19% on average (Figure 3). In the Finnish region, thinning guidelines were applied in both scenarios, and they propose thinning whenever the stocking level of a stand exceeds a recommended maximum. Therefore, in extended rotations the number of intermediate thinnings during rotation increases. However, after ten years, the thinning area starts to decrease in both scenarios due to the age-class structure of forests. In the first 10–20 years of the scenario period, almost 50% of forest area is in the stage of the first or second commercial thinnings (Figure 2). After the forests past this stage, the thinning area decreases. In the Swedish region, the annual thinning area is lower in the EXT scenario than in BAU due to the longer rotation length in EXT. According to management guidelines applied in Swedish scenarios, there is a maximum top height for thinning. Therefore, the number of thinnings is equal in both scenarios, because the top-height rule prevents later thinnings in EXT, which in turn, results in a 16% decline in the thinning area compared to BAU.

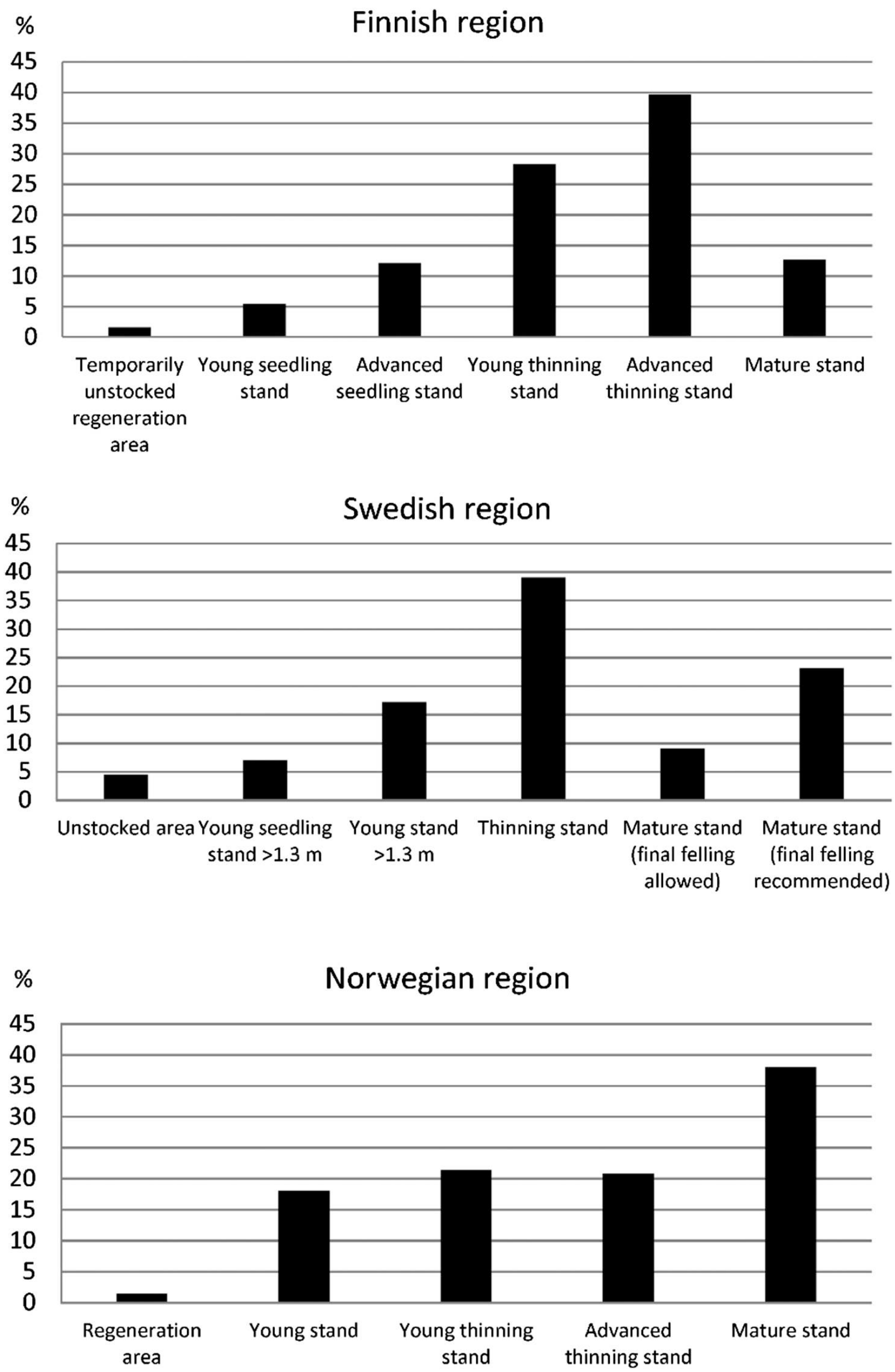

Figure 2. Distribution of forest area into the development classes in three regions.

In the Swedish region, there is a peak in the thinning area during 20–30 years in both scenarios, when the large area of young stands (Figure 2) reaches the thinning stage. In the Norwegian region, there is a slight increase (17%) in thinning area, on average. In all the regions, the temporal changes in the harvesting area are not only affected by rotation length, but the age-class structure of the forest region also has a noticeable effect on the temporal pattern. In the Finnish region, the total harvesting area of the EXT scenario is larger than in the BAU scenario during the first 20-year period due to the increase in thinning area. Over the whole 50-year period the total area of annual harvesting in the EXT scenario is smaller than in the BAU scenario, being 90%, 78%, and 83% of the harvesting area in the BAU scenario in the Finnish, Swedish, and Norwegian regions, respectively.

Harvesting removals

The lengthening of rotations decreases harvested volumes (Figure 4, Table 2). During the 50-year study period annual removals in EXT are 26% smaller than in BAU in the Finnish

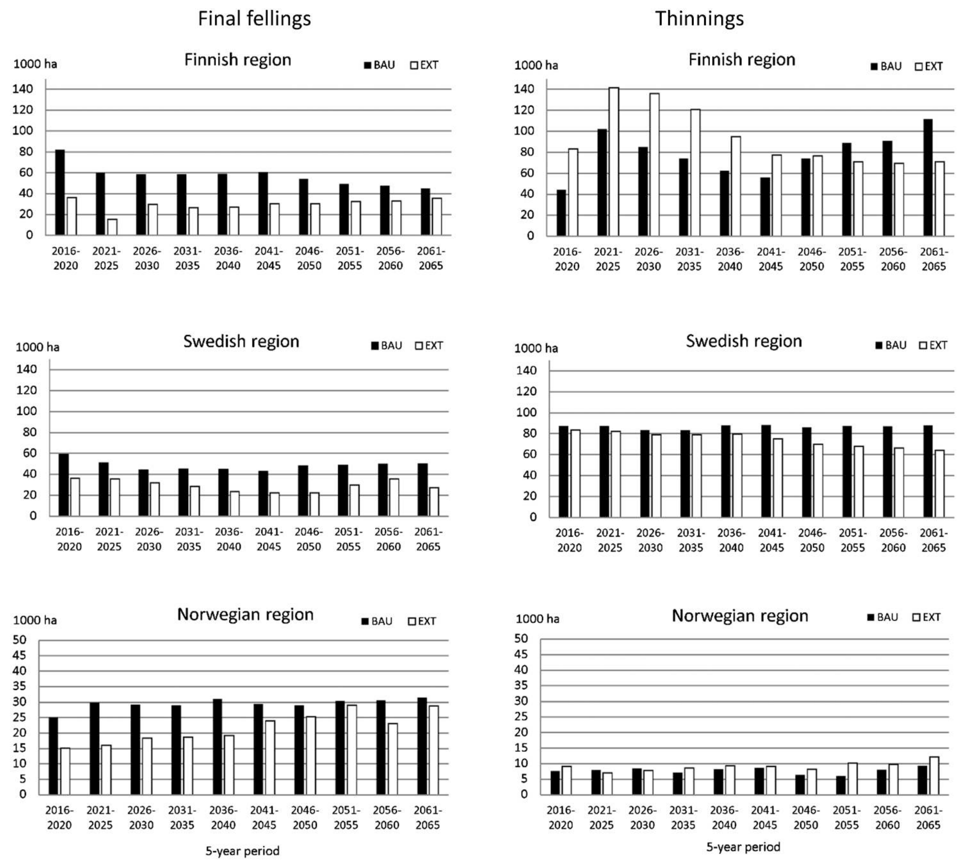

Figure 3. Mean annual harvesting area by 5-year periods and by harvesting types (i.e. final fellings and thinnings) in BAU and EXT scenarios (1000 ha a^{-1}).

and Swedish regions, and 13% smaller in the Norwegian region. There are considerable differences in removed volumes between the regions due to differences in site productivity, intensity of forest management, and development-class distributions (Figure 2). In the BAU scenario, mean annual removals per forest hectare are largest in the Finnish region (5.9 m^3 ha^{-1} a^{-1}), followed by the Swedish region (4.1 m^3 ha^{-1} a^{-1}) and the Norwegian region (2.4 m^3 ha^{-1} a^{-1}). The share of annual harvesting removals of the total standing volume of the regions' forests in the BAU scenario is 3.4%, 2.2%, and 1.9% in the Finnish, Swedish, and Norwegian regions, respectively.

The age structure of forests in a given region is reflected in the temporal distribution of harvested volumes in both scenarios. In the Norwegian region, most of the removed volume is harvested in final fellings. There is a high proportion of mature forests at the beginning of the study period, which will be harvested during the nearest decades. In the BAU scenario, final fellings will be carried out earlier than in the EXT scenario. Therefore, there is a large difference in the final-felling areas and harvested removals between the scenarios at the beginning of the study period, but it decreases towards the end of the 50 years (Figures 3 and 4).

Development of natural mortality and deadwood production

In production forests natural mortality and the amount of deadwood are usually rather low. According to NFI measurements, obtained mean volumes of deadwood in the regions were 4.8, 6.6, and 10.7 m^3ha^{-1} in the Finnish, Swedish, and Norwegian regions, respectively (Table 1).

The results of the BAU scenario show that at the beginning of the 50-year study period, annual mortality rates in all regions are at the same level varying from 0.5 to 0.6 m^3 ha^{-1} a^{-1} (Figure 5). In the Finnish and Norwegian regions, mean annual mortality rates increase during the first 30–35 years, but the increase levels off towards the end of the study period. In the Swedish region, there is no notable increase in mortality during the first 30 years, but thereafter mortality starts to increase. The trend may be affected by a large share of young stands in the Swedish region (Figure 2). In each region, annual harvesting removals were smaller than growth resulting in the increase in stocking levels along with increasing mortality.

The temporal trend in mortality rates is clearer in the EXT scenario than in the BAU scenario. By the end of the study period rates of annual mortality in the EXT scenario are 27%, 38%, and 24% greater than in BAU scenario in the Finnish, Swedish, and Norwegian regions, respectively (Figure 5). However, in the Swedish region, the absolute mortality rates are at lower levels compared with the Finnish and Norwegian regions.

In this analysis, the decomposition of deadwood is not included. Therefore, only the cumulative amount of produced deadwood due to mortality is reported. The natural mortality rate directly affects the production of deadwood (Figure 6). The difference in deadwood production between EXT and

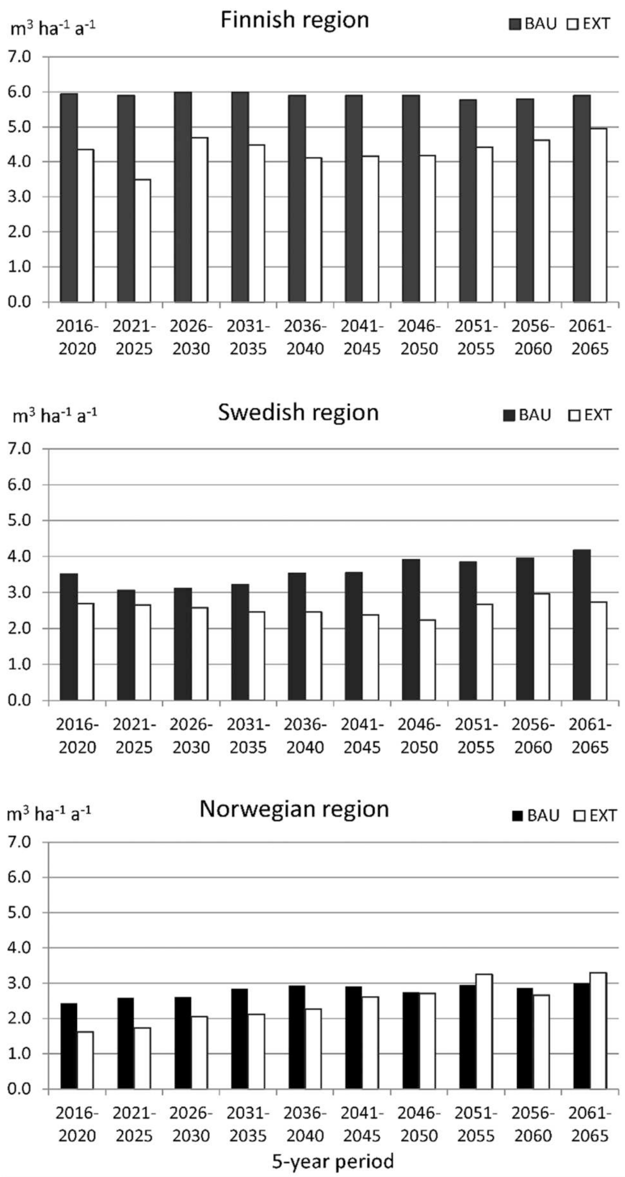

Figure 4. Mean annual harvesting removals by 5-year periods in BAU and EXT scenarios ($m^3\ ha^{-1}\ a^{-1}$).

BAU scenarios shows how much more deadwood will be produced over 50 years in the EXT scenario compared to BAU. The difference is substantial, and it increases steadily during the study period in all three regions. Although the decomposition of deadwood is not taken into account in this analysis, the results clearly show that the amount of deadwood markedly increases, when the shift to extended rotation takes place in forest management.

Carbon sequestration of the growing stock

Extended rotations increase the carbon storage of the growing stock in each region (Figure 7, Table 2). The increase in the volume and biomass of the growing stock is greater in the EXT scenario than in the BAU scenario resulting in an increasing difference in carbon storage between scenarios towards the end of the 50-year study period, especially in the Finnish and Swedish regions. By

Table 2. Forecasted development of forest characteristics by scenarios in the study regions in Southern Finland, Central Sweden, and South-Eastern Norway.

	Finnish region		Swedish region		Norwegian region	
	BAU	EXT	BAU	EXT	BAU	EXT
Mean annual removals, mill m^3						
2016–2025	25.2	16.7	19.2	15.6	9.2	6.1
2026–2035	25.5	19.5	18.4	15.1	9.9	7.6
2036–2045	25.1	17.6	20.4	13.9	10.7	9.0
2046–2055	24.8	18.3	22.2	14.3	10.4	10.9
2056–2065	24.9	20.4	23.3	16.5	10.7	10.9
Mean annual mortality, mill m^3						
2016–2025	2.8	2.9	2.9	3.0	2.8	2.9
2026–2035	3.2	3.7	3.0	3.3	3.8	4.0
2036–2045	3.6	4.3	3.3	3.9	4.5	5.2
2046–2055	4.4	5.2	3.8	4.7	4.9	5.8
2056–2065	4.7	5.9	4.1	5.7	5.0	6.1
Volume of the growing stock, mill m^3						
2016–2025	693	693	785	821	506	506
2026–2035	721	822	856	932	546	581
2036–2045	738	925	939	1065	560	631
2046–2055	766	1044	1009	1215	550	651
2056–2065	810	1140	1059	1343	534	639
Carbon balance of the growing stock, Tg CO_2 eq a^{-1}						
2016–2025	−1.0	−12.8	−2.7	−10.0	−5.7	−11.1
2026–2035	−2.4	−11.4	−9.3	−13.6	−1.7	−6.9
2036–2045	−4.1	−13.0	−9.9	−17.1	1.9	−2.1
2046–2055	−5.5	−10.4	−7.6	−18.3	2.8	2.3
2056–2065	−7.8	−6.2	−6.1	−13.4	3.3	3.6

the end of the 50 years, the difference in carbon storage between EXT and BAU is largest in the Finnish region (32%) followed by the Swedish (25%) and the Norwegian (18%) regions.

In the Finnish and Swedish regions, the volume growth of forests exceeds the total drain (i.e. the sum of harvesting removals and mortality) throughout the study period. Thus, the carbon storage of forests increases steadily in both scenarios. However, in the Norwegian region carbon storage increases only during the first 25 years, but then begins to steadily decrease in both scenarios (Figure 7). This can be, at least partly, explained by the age structure of forests. In the Norwegian region, almost 60% of the forest area is dominated by mature stands or advanced thinning stands. They will reach the stage of final felling during the forthcoming decades, which will strongly decrease the total volume and carbon storage of the region's forests.

The changes in the carbon storage of living trees (Figure 7) reflect in carbon balance of the growing stock (Figure 8). The carbon balance describes the change in the amount of carbon storage per time unit. It shows whether a system acts as a sink or a source of carbon. We calculated the carbon balance of the growing stock by 5-year periods for both scenarios.

In the Finnish and Swedish regions, forests are carbon sinks in both scenarios over the whole study period due to the steady increase of the growing stock. In the Finnish region, advanced thinning stands in BAU scenario reach the stage of final felling earlier than in EXT scenario. This will slow down the increase of the carbon storage in BAU, and results in a large difference in carbon balance between the scenarios during the first 30 years of the study period. Thereafter final fellings, in turn, increase in the EXT scenario and

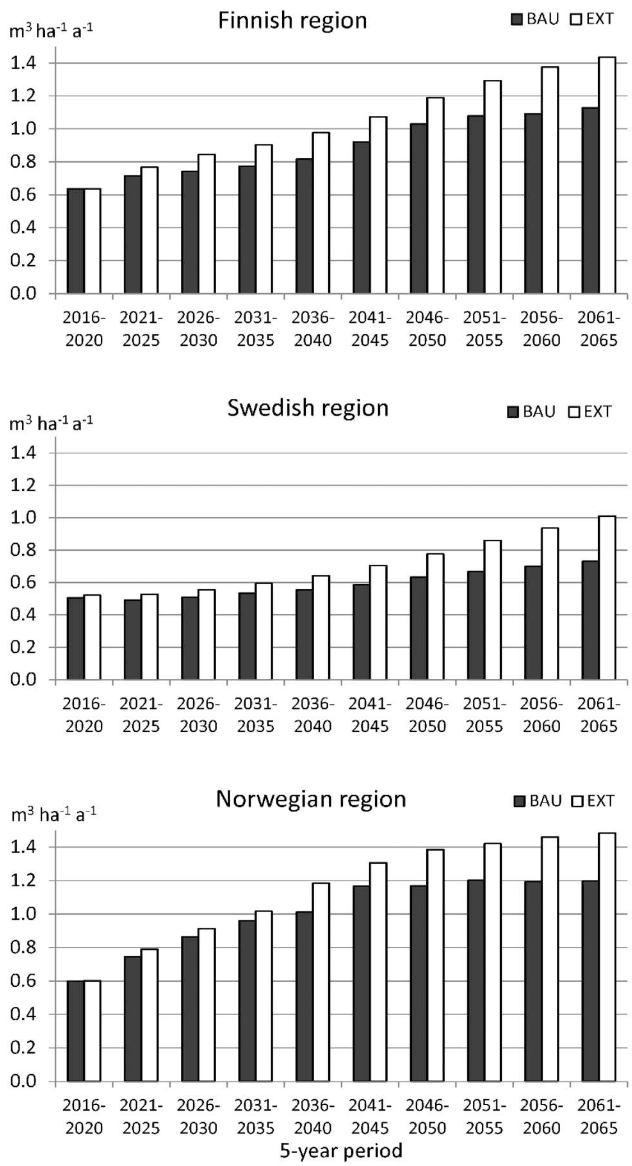

Figure 5. Mean annual mortality rates by 5-year periods in BAU and EXT scenarios (m^3 ha^{-1} a^{-1}).

decrease the difference in carbon balance between the scenarios. In the Swedish region, such a trend in carbon balance is not yet visible in the 50 years due to the younger age structure of the forests. However, there is a decreasing trend of carbon sink in the BAU scenario towards the end of the study period because of an increase in final fellings. In the Norwegian region, the carbon sink will turn into a carbon source during the second half of the 50-year study period in both scenarios. A large area of mature stands will be harvested at the beginning of the study period, which decreases the amount of growing stock (Table 2). In the EXT scenario, a similar pattern is delayed due to longer rotations.

In general, carbon balance is more favourable in EXT than in BAU scenario in all the regions, as expected. The differences in the mean annual carbon sinks over the whole study period between EXT and BAU scenarios are 1.6, 1.3, and 0.7 Mg CO_2eq ha^{-1} for the Finnish, Swedish, and Norwegian regions, respectively.

Trade-offs between different management goals

Carbon sequestration and harvesting removals

The increase in carbon sequestration and production of deadwood in production forests can be achieved by lengthening rotations, but only at the expense of harvesting removals (Table 2). We estimated trade-offs between timber production and an increase in carbon sequestration, as well as between timber production and an increase in deadwood production. In this study abatement cost was not estimated in monetary terms. Instead, we calculated the cost in terms of a decrease in harvesting removals in the EXT scenario compared to BAU.

Transition to extended rotations in forest management causes an immediate and noticeable decrease in harvesting removals, but, a noticeable strengthening of the carbon balance of the growing stock. We calculated the ratio between the decrease in annual harvested volumes (m^3 ha^{-1} a^{-1}) and the annual increase in carbon storage (Mg CO_2 eq ha^{-1} a^{-1}). The ratio shows how much annual harvested volumes (m^3 ha^{-1} a^{-1}) decrease when annual carbon sequestration of stocking increases by one Mg CO_2 eq ha^{-1}. During the 50 years, the average ratio is highest in the Finnish region, equal to 0.98, followed by the Swedish region, 0.79. The lowest ratio is in the Norwegian region, being 0.51.

In BAU scenario the proportion of annual harvesting volumes of the total growing stock volume is 3.4%, 2.2%, and 1.9% in the Finnish, Swedish, and Norwegian regions, respectively. The abatement cost of shifting to extended rotations seems to be proportional to the decrease in the intensity of harvesting and the reduction in harvested volumes. Both the absolute and relative reduction of harvesting removals are largest in the Finnish region followed by the Swedish and Norwegian regions.

Production of deadwood and harvesting removals

The effect of the transition to extended rotations on natural mortality and deadwood production is less pronounced than the effect on carbon balance. The increase in mortality rates in the EXT scenario is negligible during the first ten years of the study period, but starts then to increase steadily (Table 2, Figure 6). From the beginning of the study period, it takes 16 years until the deadwood accumulation in the EXT scenario is one cubic metre higher than that in the BAU scenario in the Finnish region. In the Swedish region, a similar difference is achieved after 22 years, and in the Norwegian region after 21 years.

During the whole 50-year period, the mean annual increase of deadwood is 0.16, 0.12, and 0.14 m^3 ha^{-1} a^{-1} in the Finnish, Swedish, and Norwegian regions, respectively. Correspondingly, the mean annual harvesting removals by regions decrease by 1.56, 1.00, and 0.36 m^3 ha^{-1} a^{-1}. The ratios between the decrease in annual harvested volumes (m^3 ha^{-1} a^{-1}) and annual increase in deadwood accumulation (m^3 ha^{-1} a^{-1}) depicting abatement costs in terms of harvested volumes are 9.9, 8.2, and 2.4 for the Finnish, Swedish, and Norwegian regions, respectively. The result is analogous to the abatement cost of increasing carbon

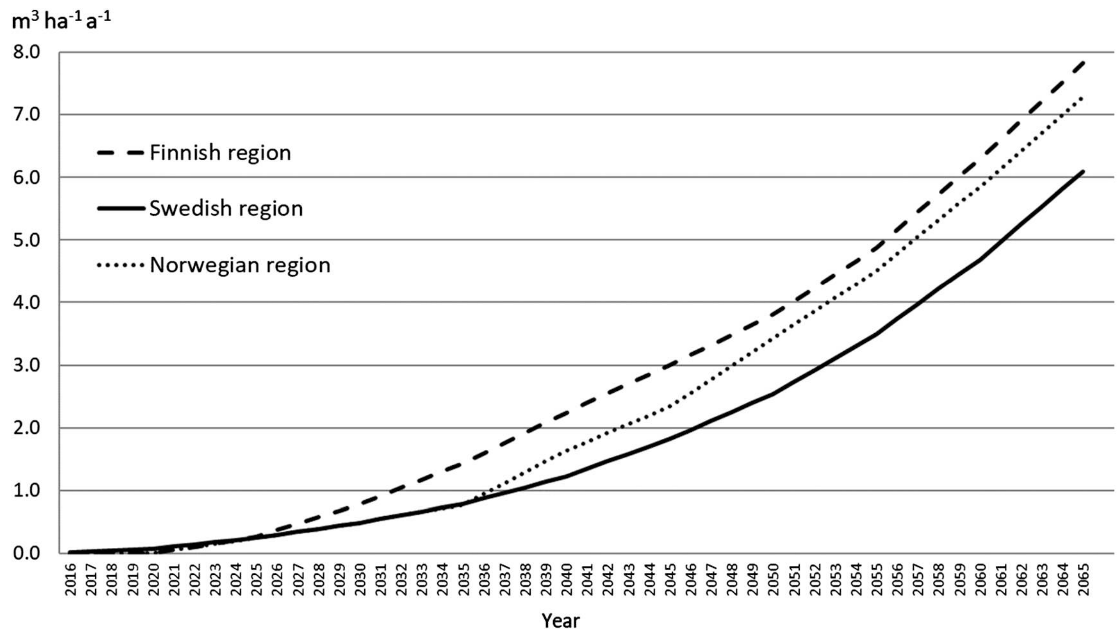

Figure 6. Difference of accumulation of deadwood volume between BAU and EXT scenarios during the 50-year study period (m^3 ha^{-1} a^{-1}). The actual amount of deadwood is smaller because decomposition is not taken into account.

sequestration. The loss in removals is greater in the Finnish and Swedish regions, where forest management and harvesting activities are more intensive than in the Norwegian region.

Discussion

Approach

We assessed the long-term effects of the alternative forest-management strategies on wood production, deadwood production, and carbon sequestration of living trees in large areas of production forests in three countries covering altogether 14 million hectares of Nordic forests available for wood production. As the outcome of our analyses, comparable results on the consequences of management alternatives for large forest areas in Finland, Sweden, and Norway are reported for the first time. However, the selected regions from three countries represent geographically restricted areas and different types of forest structures, growth conditions, and intensity of forest management. Therefore, the results from the three regions cannot be generalized to the country level, neither are they applicable to comparisons between the countries.

We used NFI data in the analyses to represent the current state of forests in each country. It ensures that scenarios are based on the best available representative description of regions' forest resources. In scenario building, similar management alternatives were applied in each region. However, we allowed some differences in the details of region-wise management regimes. The aim was to construct feasible management regimes for each region, which agree with locally prevailing management guidelines and common practices in forestry.

We applied established simulation and planning tools, which have been tested for reliable performance when applied to production forests. Despite the differences between sub-models of Heureka-Regwise, Motti, and SiTree, the modelling approaches and the overall structure of the models are similar. In the development of each model, established growth and yield modelling methods have been applied.

Limitations

The effect of climate change was not included in the analysis, although models for predicting the effects of climate change on forest growth are available in Motti (Matala et al. 2005), Heureka (Subramanian et al. 2018), and SiTree (Antón-Fernández et al. 2016; Antón-Fernández and Astrup 2022). According to the model's predictions, forest growth in the Nordic countries is predicted to increase as a result of climate change. On the other hand, climate change is likely to increase the risk of various biotic and abiotic damage (de Groot et al. 2022), which, in turn, reduces growth. Unfortunately, models predicting the magnitude of forest damage are not yet available for large-scale calculations. Therefore, we decided not to include only growth-enhancing model predictions in this analysis.

The average growth rates of trees predicted by the growth models of Motti, Heureka, and SiTree represent growth rates measured in modelling data. The use of these growth rates implies the assumption that the effect of climate change is similar for BAU and EXT scenarios. However, this assumption may not be valid, because extended rotations can increase the risk of forests to abiotic and biotic damage. This needs to be carefully considered when interpreting the results.

The rotations of the EXT scenario are noticeably longer than the currently recommended rotations for production forests. The risks of biotic and abiotic forest damage increase along with the maturing of production forest stands (Honkaniemi et al. 2017). In addition to the stand age, the

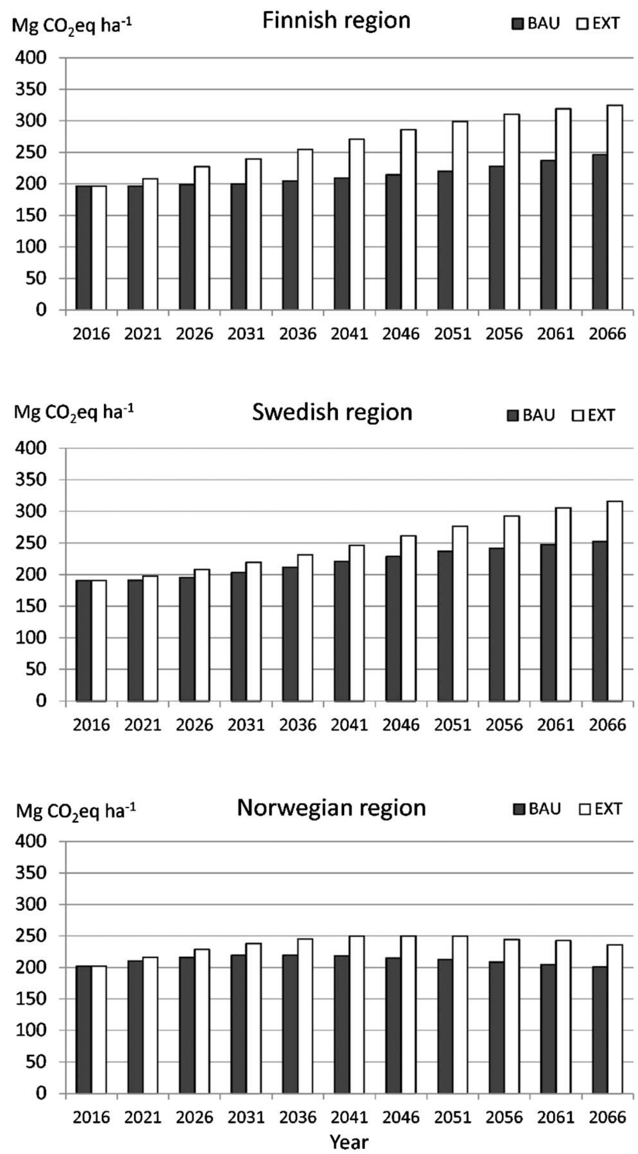

Figure 7. Development of mean carbon storage of the growing stock in BAU and EXT scenarios during the 50-year study period (Mg CO_2 eq ha^{-1}).

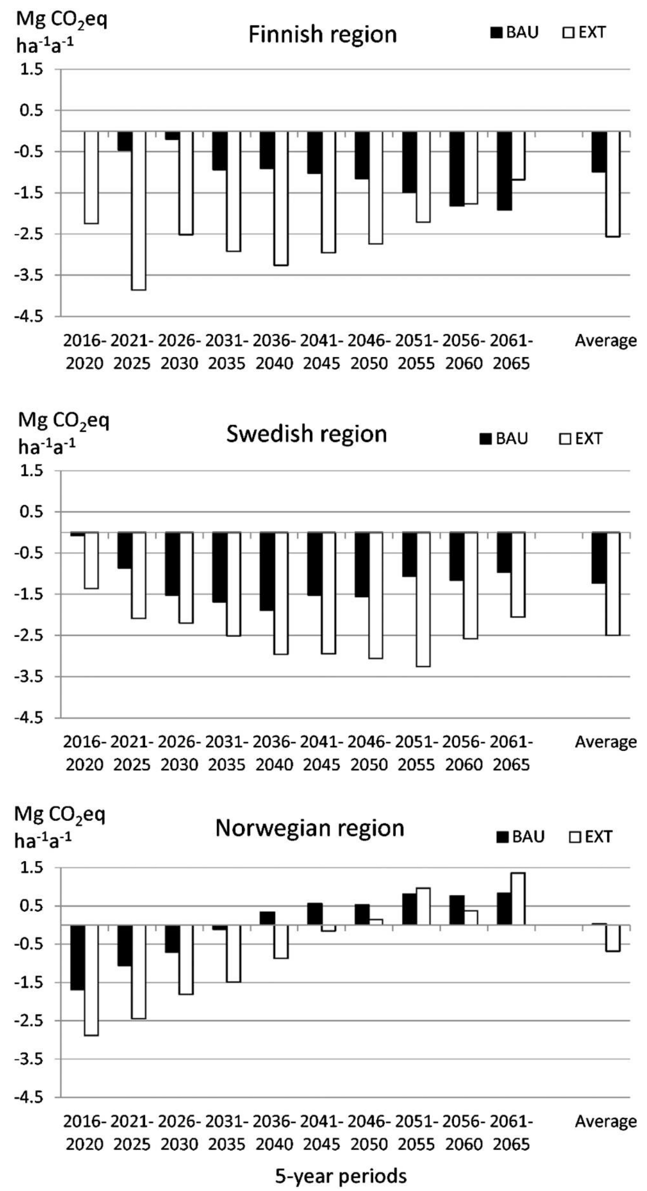

Figure 8. Development of carbon balance of growing stock by 5-year periods in BAU and EXT scenarios (Mg CO_2 eq ha^{-1}).

susceptibility to damage depends on many factors in the growth environment and stand properties. In the Nordic countries, the most susceptible forests are advanced and mature Norway spruce stands, especially in the areas where pathogens causing root rot occur commonly (Mattila and Nuutinen 2007). The other major agents of damage in spruce stands are bark beetles, which have increased in recent years due to a more favourable climate for their reproduction (Seidl et al. 2017). Forests degraded by pathogens are also more susceptible to storm damage. Storm damage, in turn, increases the risk of bark beetle outbreak (Honkaniemi et al. 2018). The species-specific mortality models applied in simulations will account partly for the effects of forest damage. Model predictions are sensible to the ageing of forests, as well as stand-density-related mortality (Siipilehto et al. 2020, 2021). However, the large, epidemic occurrence of forest damage has not been considered in our calculations.

It is likely that climate change will affect the development of forests under extended rotation management, especially in forest areas in Finland and Norway, where Norway spruce is a dominating tree species. The actual mortality is likely to be higher than predicted especially for the EXT scenario. Therefore, the increase in carbon storage of the growing stock is likely to be lower than predicted in the EXT scenario.

We restricted the analysis of carbon sequestration to above- and below-ground carbon of living trees. However, forest management practices also affect soil carbon storage. Thinnings and final fellings are the most common management practices in production forests with well-known effects on the carbon sequestration of tree stands. Moderate thinnings have been found to have only minor effects on soil carbon stocks (Clarke et al. 2015; Zhang et al. 2018; Mäkipää et al. 2023). Final fellings in stem-only harvesting decline soil carbon by 10–20% depending on the site quality and dominant tree species (Liski et al. 1998; Peltoniemi et al. 2004; Clarke et al. 2015). According to Eliasson et al. (2013), the overall effect of stem-only harvesting at the landscape level may be smaller than in individual stands. Thus, extended rotations are likely to increase soil carbon storage, because the annual final-felling areas are smaller than in management using prevailing rotations. Lindroos et al. (2022) reported results on the development of soil carbon stocks from long-term experiments showing the increase in soil carbon along with increasing stand volume. During extended rotation, an advanced stand with a high stocking level is grown for a longer period, which benefits the carbon storage of the growing stock and forest soil.

We derived deadwood production directly from natural mortality and did not include the decomposition of deadwood in the analyses. Thus, deadwood storage in forests is smaller than accumulated mortality. However, in Nordic boreal forests dominated by coniferous tree species decomposition of deadwood is slow. Mäkinen et al. (2006) developed models for deadwood dynamics in managed as well as dense unthinned stands based on extensive empirical data. They showed that after 50 years from the death of a tree, the remaining fraction of stem volume is still ca. 50% for Scots pine and Norway spruce. Although the results obtained do not directly describe the amount of deadwood, they do describe the significant impact of extended rotation on the occurrence of deadwood in production forests.

Key findings

The shift from prevailing rotation to extended rotation lengths would mean a marked decrease in final-felling area as well as in harvesting removals in all regions. Socioeconomic effects will be considerable. For wood supply to the forest industry, the effect would be significant. First, there will be a decrease in harvesting removals of industrial wood by 26% in the Finnish and Swedish regions and 13% in the Norwegian region. Such a sizeable reduction is likely to create the need for adaptive measures within the forest industry, such as a significant decrease in industrial wood consumption, changes in the product portfolio, and/or the need to import wood from outside the Nordic countries.

For forest owners longer rotations would mean decreased profitability of forest management due to decreased harvested volumes and harvesting incomes. This loss can be partly compensated by an increased share of more valuable saw timber in final fellings. Further, if storing carbon in the forests will become a source of income for forest owners, it improves the profitability of extended rotation management from the forest owners' perspective.

Extended rotations in production forests have favourable consequences on forest biodiversity. Due to the longer lifetime of trees, the amount of old and large trees increases. It is especially important in stands with broadleaved tree species, which have high biodiversity value. An increase in natural mortality results in an increased amount of decaying deadwood in forests, which is highly important to many endangered species (Jonsel et al. 1998; Siitonen 2001). Deadwood volumes in old natural forests of Fennoscandia have been reported to vary between 60 and 120 m^3ha (Siitonen 2001; Ranius et al. 2004; Aakala 2010; Shorohova and Kapitsa 2015). The deadwood volumes in the study regions based on NFI measurements (Table 1) are similar to those reported in intensively managed boreal forests, i.e. less than 10% of comparable types of natural forests (Siitonen 2001). Our results show that extended rotation increases the rate of natural mortality by 15–20%, on average, being an important measure in aiming to improve biodiversity in production forests. Further, at the forest landscape level, a decrease in the final-felling area due to extended rotations improves the living conditions of those species, which require continuous forest cover, for example, bilberry (*Vaccinium myrtillus*) and epiphytic lichens (Roberge et al. 2016).

There were differences in the development of carbon storage of the growing stock between the three regions. In the Finnish and Swedish regions, the general pattern of changes in the carbon storage in BAU and EXT scenarios were rather similar, and the results are in agreement with the recent national-scale scenarios for Finland (Koljonen et al. 2020) and Sweden (Eriksson and Bergh 2022). In both regions, the forest crabon stock increases throughout the 50-year period, but the increase is faster in the EXT scenario compared to the BAU scenario. In the Norwegian region, carbon storage slightly increases only during the first 15 years, but decreases thereafter in both scenarios. A similar pattern was observed in the country-level scenarios by Hylen et al. (2022).

Conclusions

We evaluated the performance of extended rotations as a measure to strengthen sustainable forestry. The results suggest that lengthening of prevailing rotations in production forests results in trade-offs between wood production and other management goals.

There is a noticeable trade-off between carbon sequestration and harvesting removals when shifting to extended rotations. The abatement cost will be higher the more intensive wood production is practised in the region. The abatement cost in terms of loss of harvesting removals was highest in the Finnish region with high demand for industrial wood and favourable conditions for intensive wood production.

The trade-off between wood production and deadwood production is not as straightforward as the trade-off between wood production and carbon sequestration. The results show that longer rotations increase mortality and deadwood volumes in production forests, although at the cost of commercial wood production. However, the value of deadwood for biodiversity does not depend solely on the volume of deadwood, but also on other characteristics, which were not addressed in this analysis, such as the stage of decomposition rate, and the size and species of decaying trees (Siitonen et al. 2000).

Lengthening of rotations alone may not be the most efficient way to increase carbon sequestration of production forests. Volume growth and carbon storage of the crowing stock can be effectively regulated by varying thinning intensity. Results from long-term thinning experiments show that heavy thinnings noticeably decrease stand volume growth, especially in Scots pine stands (Mäkinen and Isomäki 2004a, 2004b; Nilsson et al. 2010). In Finland and Sweden, prevailing thinning recommendations result in sparse stocking levels, which are justified for economic reasons, but are inefficient from the point of view of stand growth and yield. More frequent and less intensive thinnings along with extended rotations could be a compromise that would allow the different objectives to be reconciled in forest management.

Disclosure statement

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