Scenario analyses for the effects of harvesting intensity on development of forest resources, timber supply, carbon balance and biodiversity of Finnish forestry

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Abstract

We used national scenario analyses to examine the effects of harvesting intensity on the development of forest resources, timber supply, carbon balance, and biodiversity indicators of Finnish forestry in nine 10-year simulation periods (90-year simulation period) under the current climate. Data from the 11th National Forest Inventory of Finland were used to develop five even-flow harvesting scenarios for non-protected forests with the annual harvest ranging from 40 to 100 million m^3. The results show that the highest annual even-flow harvest level, which did not decrease the growing stock volume over the 90-year simulation period, was 73 million m^3. The total 90-year timber production, consisting of harvested volume and change in growing stock volume, was maximized when the annual harvest was 60 mill. m3. Volume increment increased for several decades when harvested volume was less than the current volume increment. The total carbon balance of forestry was the highest with low volume of harvested wood. Low harvested volume increased the values of biodiversity indicators, namely volume of deciduous trees, amount of deadwood and area of old forest.

Keywords: Biodiversity, Bioeconomy, Carbon balance, Even-flow harvesting targets, National Forest Inventory, Timber supply

1. Introduction

There is a pressure to increase wood production in Finland and elsewhere in Europe in order to fulfill the increasing demand for wood biomass in the growing forest bioeconomy. Increased wood production is also needed to move towards low-carbon and resource-efficient society in which fossil resources are substituted by renewables to mitigate climate change (The Finnish Bioeconomy Strategy 2014; Sathre et al. 2010; Scarlat et al. 2015; Kilpeläinen et al. 2016). However, at the same time other ecosystem services, such as forest biodiversity, should be secured and maintained.

The total forested land area in Finland is 26.2 million ha and the current total growing stock volume is 2357 million m^3, of which about 90% is in commercial forests (Finnish Statistical Yearbook of Forestry 2014). In 2013, the annual gross volume increment of the growing stock was 104.4 million m^3, of which 96.2 million m^3 was in forests available for cuttings. The annual timber harvest was 65.3 million m^3 (Finnish Statistical Yearbook of Forestry 2014). Both the growing stock volume and the volume increment have increased for several decades, mainly because the harvested volume has been smaller than the volume increment. Also climate change is expected to increase forest growth and timber supply from Finnish forests (Kellomäki et al. 2008). According to the Finnish Statistical Yearbook of Forestry (2014), the maximum annual sustainable drain of timber is 73 million m^3 yr^{-1}, and the drain of energy biomass is 21 million m^3 yr^{-1} (including small-sized stem wood, foliage, stumps and coarse roots) for the period 2010-2019. These figures are clearly higher than the current removal rates.

In the EU, the bioeconomy had a turnover of about € 2 trillion in 2012 and it employed over 22 million people, and these numbers are expected to increase remarkably (European Commission 2012). According to Scarlat et al. (2015), the bioeconomy market in the EU was about € 2.4 trillion in 2014. In Finland, the current bioeconomy output is approximately € 65 billion and its share from exports is about 25% (Finnish Bioeconomy Strategy 2014). More than half of the bioeconomy relies on forest utilization. The Finnish Bioeconomy Strategy (2014) aims at increasing the output of Finnish bioeconomy to € 100 billion and creating 100 000 jobs within the next 10 years. This requires considerable increase in the harvests of Finnish forests. Numerous industrial investments have already been made, are under a way, or are planned in the Finnish forest bioeconomy sector. Depending on realized investments, the Finnish forest industry may need 10–30 million m^3yr^{-1} more wood in the coming years.

Increasing harvests are likely to increase the environmental impacts of forestry. For example, the amount of dead wood and deciduous wood will most probably decrease, which affects the biodiversity of forests (Juutinen et al. 2006; Tikkanen et al. 2007; Bradford and D'Amato, 2012; Gamfeldt et al. 2013). Especially large dead trees and aspens (*Populus tremuloides*) are key elements for many endangered species and for overall biodiversity (e.g., Sahlin and Ranius 2009; Similä et al. 2013). In managed forests, the amount of dead wood is usually low from the forest biodiversity point of view compared to unmanaged forests. For example, in southern Finland the quantity of coarse woody debris (CWD) is, on average, less than 10% (< 4 m^3 ha^{-1}) of its amount in natural forests (CWD > 40 m^3 ha^{-1}, Siitonen et al. 2001; Junninen et al. 2006). On the other hand, climate change is expected to intensify natural disturbance regimes in forests (e.g., by wind storms, forest fires and bark beetle damages), of which biodiversity will benefit while other ecosystem services, like timber production, may suffer (Jönsson et al. 2009; Subramanian et al. 2016; Thom and Seidl 2016).

In forest-rich countries like Finland, forest-based bioeconomy can play an important role in climate change mitigation. This is because growing forests sequestrate carbon, act as carbon storage and provide wood to substitute fossil-intensive materials, products and energy (Matala et al. 2008; Kärkkäinen et al. 2009; Sathre et al. 2010; Hynynen et al. 2015; Kilpeläinen et al. 2016). The total carbon balance of forestry is affected by changes in several carbon pools, namely the carbon of growing stock (living above- and below-ground forest biomass), above- and below-ground dead organic matter (soil carbon) and wood-based products (Malmsheimer et al., 2011; Verified carbon standard, 2013; Pukkala, 2014). Emissions from fossil fuels can also be reduced by cascade use of wood material, e.g., by recycling waste paper and using wood from demolished buildings as fuel feedstock (Werner et al. 2010).

Previously, Sievänen et al. (2014) studied the carbon balance of Finnish forestry, considering both mineral soils and peatlands. Lundmark et al. (2014) analyzed the carbon balance of Swedish forestry. Matala et al. (2009) and Hynynen et al. (2015) studied temporal variations in the carbon stock of Finnish forests. In the long run, managed forests are expected to be better carbon sinks than unmanaged forests were losses by natural mortality would increase and the net increment in living biomass will eventually turn zero (Smyth et al. 2014; Hynynen et al. 2015; Pukkala 2016).

Scenario analysis offers a means to study the effects of harvesting intensity on the development of forest resources, timber supply, carbon balance of forestry and biodiversity indicators. A scenario can be considered as a vision of the future, or a projected sequence of events, for instance in a detailed forest management plan. According to a recent national scenario analysis by Hynynen et al. (2015), it is possible to increase the average annual cutting volume in Finland by up to 40% during 100 years, by increasing the intensity of forest management and utilization.

In this work, we used national scenario analyses to examine the effects of harvesting intensity on the development of forest resources, timber supply, carbon balance, and biodiversity indicators of Finnish forestry in nine 10-year simulation periods (90 years in total) under the current climate. The study developed five even-flow harvesting scenarios where the annual harvest ranged from 40 to 100 million m^3, i.e. from clearly lower to clearly higher than the present drain. We used forest data from the National Forest Inventory of Finland (NFI11), excluding protected forests. The impacts of varying even-flow harvesting targets on the carbon balance of forestry were analyzed, including all the carbon pools listed by the International Panel on Climate Change (IPCC 2000). We used the amount of dead and deciduous wood, and the areas of mature and old forest as biodiversity indicators.

2. Material and methods

2.1 Forest data

Forest data used in this study consisted of a sub-sample of the sample plots of the 11th National Forest Inventory (NFI11) of Finland, conducted between 2009 and 2013. In NFI11, a systematic grid of sample plot clusters covered the whole country. One sample plot (number 3) from every cluster was selected for this study. Plots situated in protected forests were excluded. Sample plots were divided into three groups based on their geographical location so that plots situated in the earlier-applied forestry center areas of southern (1–6), central (7–10) and northern Finland (11–13) constituted their own calculation regions. As a result, the dataset included 1890 sample plots for southern Finland, 1393 plots for central Finland and 1402 plots for northern Finland (Table 1). Analyses were performed separately for these three regions, and national results were combined from regional results. The area that one sample plot represents was obtained by dividing the total forested land area of the region used for timber production by the number of sample plots located in that region.

Table 1.

The selected sample plot data were imported into Monsu software (Pukkala 2011), which was used as the platform for the scenario calculations. Data on trees were imported to Monsu as tree lists. Variables used for sample trees were: tree species, diameter at breast height (dbh), height and number of trees per hectare. However, some of these variables were not collected in the field inventory. The number of trees per hectare, represented by the sample tree, was calculated from dbh and the used basal area factor. In addition, in NFI11 only every 7^{th} relascope-sampled tree was measured for height. To mimic the tree size variation of sapling stands (mean diameter less than 8 cm), one NFI11 sample tree was divided into three sample trees, each representing 1/3 of its initial frequency. One tree had dbh and height 20% lower than the original and another had a dbh and height 20% higher.

2.2 Calculation of tree height

The missing heights for trees larger than 8 cm in dbh (46473 trees) were imputed using a nonlinear mixed-effects model based on the Näslund's (1937) function, which was recently suggested by Mehtätalo et al. (2015) for general use. The model was fitted separately for the three main species using the species-specific sample tree data (3183 Scots pines (*Pinus sylvestris*), 1919 Norway spruces (*Picea abies*) and 1536 silver and downy birches (*Betula pendula* and *Betula pubescens*) and other broadleaved trees). The modeling followed the procedures described in Mehtätalo et al. (2015). The two parameters of the Näslund's (1937) function were modeled using linear submodels and random plot effects. The following variables, with appropriate nonlinear transformations, were used as fixed predictors in both submodels: mean dbh, basal area, altitude, temperature sum and categorical site characteristics.

As the resulting height-diameter (H-D) data are used to simulate forest growth, a realistic description of the variability in the H-D relationship between and within stands is important. Therefore, all random components of the fitted model were also included in the predicted heights. Particularly, the predicted random effects of the plot were used whenever the plot had at least one tree of the species under study for prediction of the random effect. If no sample trees were available for the prediction of random effects, the random effects were simulated using bivariate normal distribution with an estimated variance-covariance matrix of random effects to generate realistic variation in the H-D relationship between stands. In addition, normally distributed residual error, using the estimated error variance, was simulated for each predicted height to generate realistic variation of tree heights within a stand. The observed height was used for the sample trees. Figure 1 illustrates the resulting data for Scots pine trees.

Figure 1.

2.3 Simulation of treatment schedules for plots

The simulation horizon was set to 90 years, and divided into nine 10-year periods. The currently recommended thinning (basal area) and final felling (diameter at breast height) thresholds in Finland (see Äijälä et al. 2014) were multiplied by 0.9 to define the earliest possible time of thinning and final felling, respectively. Additional treatment schedules were obtained by postponing cuttings. A schedule without cuttings was also simulated for each stand (sample plot). Thinnings were simulated as uniform thinning corresponding to the current trend towards using more thinning from above. Regeneration of clear cutting areas was simulated by always planting Norway spruce on herb-rich and mesic sites and Silver birch on the most fertile sites (mesotrophic herb rich sites). Sowing of Scots pine was always used on sub-xeric sites and natural regeneration for pine on poorer sites. Seedlings of various tree species were also expected to be born naturally on all sites. Tending treatment for dense seedling and sapling stands were simulated according to recommendations. The genetic growth gain of planted seedlings and sown seeds was assumed to be 5%, which is slightly lower than that observed for 1-generation seed orchards with untested plus trees in Finland (e.g., 7% for pine, see Haapanen and Mikola 2008). However, in actual forestry improved regeneration material is not always used in artificial regeneration.

The minimum lengths and top diameters of timber assortments used in logging, as well as the roadside and stumpage prices of different assortments, are presented in Table 2. Laasasenaho's (1982) taper functions were used to calculate the assortment volumes in logging. Harvesting costs were calculated using harvesting cost functions (Rummukainen et al. 1995).

Table 2.

The reported volume increment in the results of this study is the net volume increment of round wood (natural mortality is subtracted from the volume increment). Timber production was calculated by subtracting the timber volume of the current growing stock from the volume after 90 years and adding the volume of timber harvested during the 90-year simulation period.

2.4 Calibration of growth models

The models of Pukkala et al. (2013) were used to predict diameter growth, survival, and ingrowth. Height growth was simulated by using the models of Pukkala et al. (2009). The diameter increment models were calibrated based on the correction factors of the basal area growth models of the MELA system (MELA 2012 Reference ... 2013). The growth measurements of NFI11 indicated that spruce grows slightly less than the non-calibrated models predict, whereas pine and birch grow more (MELA 2015). Firstly, the MELA growth models (Hynynen et al. 2002), as implemented in Monsu, were scaled separately for different tree species using the MELA (2015) correction factors. Then, the models of Pukkala et al. (2013) were calibrated by adjusting the random stand factors of the models, separately for different tree species and regions, so that the same regional volume growth was obtained as with the scaled MELA models. After this calibration, the current annual net increment in growing stock volume (volume increment of living trees minus annual mortality) in unprotected forests was predicted to be 86.6 million m^3, both with the MELA and Monsu models.

The same growth models were used in mineral soils and peatland forests. Downward corrections were made for peatland forests on the basis of drainage class, which was available in the inventory data. The growth prediction was reduced for all other drainage classes except well-drained peatland forest with efficient drainage.

2.5 Calculation of carbon balance of forestry

Carbon balance of forestry was defined to be the difference between all sequestrated and released carbon during the calculation period. The carbon balance of forestry (TotCB) consists of changes in three carbon pools: (1) living forest biomass (CBBiom); (2) soil organic matter (CBSoil); and (3) wood-based products (CBProd). The pools listed in the IPCC carbon accounting rules were all included in the calculations of this study (IPCC 2000). The CBSoil and CBProd pools of every plot were initialized with models (Pukkala 2014) to estimate the initial amount of soil organic matter and the remaining mass of products manufactured before the start of the simulation period. The initial sizes of the living forest biomass (above- and below-ground) pools were calculated from the NFI11-based forest data using taper functions (Laasasenaho 1982), biomass models (Repola et al. 2007; Repola 2009), and basic density of wood for each tree species (Saranpää 2003). Initialization resulted in realistic differences between sequestrated and released carbon already for the first years since the decomposition of the initial carbon pools of soil and products were taken into account. However, initialization had no effect on the carbon balance differences between the scenarios. Carbon balance standards (IPCC 2000; Verified carbon standard 2013) do not require that the pools are initialized. However, the balances would have been biased without initialization (if it was assumed that the initial pool sizes were zero), leading to overestimated carbon balances for the first 10-year periods.

CBBiom was positively affected by regeneration and tree growth, whereas mortality of trees and harvesting of wood decreased it. Dead trees, residues of harvested trees and annual above- and below-ground litter production of trees increased CBSoil. Litter production was calculated from the biomasses of branches, foliage, coarse roots and fine roots, using the same tree species-specific turnover rates as in Pukkala (2014). Release of carbon through the decomposition of dead organic matter decreased CBSoil and was simulated using the Yasso07 model (Liski et al. 2009; Tuomi et al. 2011a, 2011b).

CBSoil was calculated also for peatlands. The thickness of the peat was set as one meter. This simplification does not affect the soil carbon balance of peatlands, which depends on the oxygen-rich (decomposing) layer, which is thinner than one meter. The carbon balance of peat also depends on the annual growth rate of the peat and the decomposition rate of the oxygen-rich layer. The thickness of the decomposing layer was assumed to be 5–35 cm (Laiho 2006), depending on ditching and time since ditching. The annual increment of the thickness of compressed peat was assumed to be 1 mm in undrained peatlands, and draining was assumed to decrease peat growth rate. The basic density of compressed peat was 0.35 tons/m^3. Decomposition of peat was simulated using the Yasso07 model. The parameters of the Yasso07 model (the shares of the so-called AWENH components of peat) were set in such a way that the simulated carbon emissions from peat due to decomposition corresponded to measured emissions from peatland sites (e.g., Laiho 2006; Saarnio et al. 2007; Ojanen et al. 2010). Due to a lack of research knowledge, carbon balance estimates for peatlands involved greater uncertainty than the estimates for mineral soils.

CBProd of a certain period consisted of the carbon content of the wood harvested during that period, re-use and substitution effects of products prepared from harvested wood, releases in logging, transport of harvested wood and manufacturing of wood products, and decomposition of newly prepared and old products (decomposition of the product pool). Harvested trees were divided into three assortments: saw log, pulpwood and energy wood (Table 2). These assortments were further partitioned into four end product classes: (1) sawn wood and plywood; (2) mechanical pulp and paper; (3) chemical pulp and paper; and (4) biofuel. The proportions of each end product category for saw log and pulpwood were obtained from previous studies (Karjalainen et al. 1994; Liski et al. 2001; Pukkala et al. 2011; Pukkala 2014, see Table 3) and from authors of this study. The proportions shown in Table 3 are based on future expectations, and may therefore differ slightly from those proposed in the literature.

Table 3.

The decomposition of each end product category was simulated by a decay curve:

$$Y_t = Y_0 e^{kt}, \quad (1)$$

where Y_0 is the initial mass, Y_t is the remaining mass t years later and k is the annual decomposition rate. Decomposition rates k are shown in Table 4 (Karjalainen et al. 1994; Liski et al. 2001). The decomposition rate of products refers to the product lifetime in its primary use, including the recycling of paper products. Due to recycling of paper and packing material, a rather low annual decomposition rate (0.1) was set for paper and packing material manufactured from mechanical and chemical pulp.

After the primary use the product may have a secondary use (reuse). Use of discarded sawn wood and paper products for biofuel was the only assumed reuse. It was assumed that 40% of discarded paper and packing materials and 80% of discarded sawn wood and plywood was used as biofuel with the same substitution effect as other biofuels (Pukkala 2017). The rest was assumed to decompose without substitution effects and release carbon dioxide to the atmosphere. The used substitution rate was 1.0 tC/tC for sawn wood and plywood and 0.8 tC/tC for biofuel meaning, for example, that the use of biofuel decreased the releases from fossil fuels by an amount equal to 0.8 times the carbon content of wood. Product decomposition and reuse, as well as the substitution effects were independent of the place where the products were used, i.e., exported and non-exported products were treated in the same way in calculations.

Manufacturing releases for wood-based products were adopted from previous studies of Liski et al. (2001) and Pukkala (2014). These releases were 3.2% of the carbon content of the wood product for the production of sawn wood, 13% for chemical pulp and paper, 48% for mechanical pulp and paper and 5% for biofuel (Table 4). Increasing diameter of harvested trees decreased releases from harvesting (see Pukkala 2011). Calculation of releases during transportation was based on fuel consumption of a truck for a return trip of 150 km for round wood and 100 km for biofuel.

Table 4.

2.6 Calculation of biodiversity indicators

The volume deciduous trees, biomass of dead wood and the area of old forest were used as biodiversity indicators (Kangas et al. 1996; Pukkala et al. 1997; Koskela et al. 2007). Dead wood was partitioned into two diameter classes: dbh 10–30 cm and dbh > 30 cm. Dead wood less than 10 cm in dbh was not considered in this study due to its low importance for biodiversity (e.g., Tikkanen et al. 2007; Stokland et al. 2012). The amount of dead wood was expressed as the dry mass of dead wood. The annual decomposition rate was calculated individually for each dead tree as a function of tree species and dbh using the models of Pukkala (2006), which are based on the decay information available in Tikkanen and Kouki (2007). The initial amount of dead wood was not available. Therefore, the predicted development of dead wood was only used to compare the outcomes of different cutting scenarios, not to give absolute values. In addition, the areas of “mature” and “old” forests were calculated from the simulation data. The threshold ages for old forest were set as 200, 180, 140, 120 and 120 years for Scots pine, Norway spruce, silver birch, downy birch, and aspen. The threshold ages for mature forest of these tree species were 120, 100, 80, 70 and 70 years.

2.7 Cutting scenarios

Five different cutting scenarios were developed for the plots. The basic scenario (S60) was based on the current drain level, which is about 60 million m^3 yr^{-1} of round wood at the country level (LUKE 2014). The cutting targets of S60 for saw log and pulpwood were derived by summing the realized cutting volumes of 2004–2013 (Table 5), separately for the three regions. Five million m^3 yr^{-1} was added as pulpwood-sized energy wood. The rest (left from 60 million) was assumed to be small-sized household energy wood, the amount of which was not controlled by constraints. Scenario S60 harvested different assortments as follows (million m^3 yr^{-1}): saw log 23.41, pulpwood 28.87, pulpwood sized energy wood 5.00, and household energy wood 2.72. Harvesting targets were not specified separately for different tree species.

Table 5.

The saw log and pulpwood cutting targets of 40 (S40), 80 (S80) and 100 (S100) million m^3 yr^{-1} were proportional to the cutting volumes of S60. For example, the saw log volume target for S80 was 33% higher than for S60. In addition, a scenario called SUS (sustainable) was developed where the harvested volume was the highest possible, which did not lead to decreasing growing stock volume during the 90-year simulation horizon.

2.8 Problem description and optimizations

The objective of the harvest scheduling problem was to maximize timber (saw log and pulpwood) production and profitability of forest management, with the harvested volume of saw log and pulpwood for each 10-year planning period being equal to the target (Table 5). Greater importance was given to fulfilling the cutting targets of earlier 10-year periods, so as to determine for how long it is possible to maintain a certain cutting level. The discount rate used in calculating net present value was 3%.

The best combination of treatment schedules simulated for the NFI plots was found using a hybrid method of simulated annealing (Lockwood and Moore 1992; Dowsland 1993; Bettinger et al. 2002; Öhman and Eriksson 1998) and Hero (Pukkala and Kangas 1993) heuristics (Pukkala and Heinonen 2006). The parameters and the objective function used in optimization were set separately for each optimization run. Results are reported mainly at the country level. Regional results are shown in detail in Appendix 1.

3. Results

3.1 Timber production

The country level cutting targets were met in S40, S60 and SUS (Fig. 2). In SUS, the annual cutting volume (sum of regional SUS scenarios) was 73 million m^3 yr^{-1}. The cutting target of S80 was met for six decades and the target of S100 for three decades. In northern Finland, the cutting target of S80 was met for the whole 90-year period. Shortage of saw log was the main reason for falling short of the target. The share of saw log decreased and the share of harvested spruce wood increased with growing cutting target.

Figure 2.

The volume increment during the 90-year simulation period was the higher, the lower was the even-flow cutting target, increasing for about five decades in S40 and S60 (Fig. 3). The average annual volume increment of the 90-year simulation period was the greatest in S40 (84.5 million m^3), 2.5 % higher than in S60. Timber production (harvested volume plus change in growing stock volume) was the largest in S60 (Fig. 4). Increasing the annual harvest from 60 to 73 mill. m^3 decreased timber production by 3%.

Figures 3 and 4.

3.2 Growing stock volume

At the end of the simulation period (year 2106) the volumes of total standing timber, saw log and pulpwood were clearly above their initial levels for scenarios S40 and S60. In 2106, the volume of total standing timber was 5500 million m^3 in S40 and 3751 million m^3 in S60 at the country level (Fig. 5). Scenario S80 ended up with considerably lower final volume than the initial volume. However, in the north the ending timber volume of S80 was higher than the initial value.

Figure 5.

The volume of spruce increased from the initial 631 million m^3 in all scenarios. The share of spruce increased with growing cutting targets, particularly towards the end of the 90-year simulation period (Fig. 6). In SUS, spruce became the dominant tree species after 70 years. In S40, S60, and S80 the volume of pine increased from the initial 1024 million m^3. The final shares of spruce and pine were about the same in S60 and S80. The volume of deciduous tree species decreased with the increasing cutting target and it consisted mostly of pulpwood.

Spruce usually became dominant instead of pine after about 30 years in southern Finland and after 60 years in central Finland, while pine remained dominant in northern Finland.

Figure 6.

3.3 Carbon balance

TotCB was positive during the whole 90-year simulation period for all scenarios except S100 (Fig. 7). At the beginning, relative differences between the sustainable scenarios (S40, S60, SUS) were small, becoming larger in the middle of the simulation period, and reducing again towards the end. The lower the cutting target, the higher was TotCB.

Figure 7.

CBBiom was positive over all 10-year simulation periods only in S40 and S60, in which the biomass increased steadily. CBBiom increased until the fourth period, and then started to decrease (Fig. 7). Logically, CBBiom of the SUS scenario was quite stable and close to zero due to even flow of harvested volume and non-decreasing growing stock volume. CBBiom was slightly negative in S80 and clearly negative in S100.

A positive peak was observed in CBSoil during the first period in all scenarios, which was most probably due to the tending treatments of young stands (felled young seedlings and saplings). CBSoil was positive during the whole simulation period only in scenarios S40 and S60 (Fig. 7). SUS had positive CBSoil until the sixth 10-year period and S80 until the fourth period.

Scenarios with higher cutting targets displayed better CBProd values since they resulted in the highest substitution effects and stored more carbon in wood-based products (Fig. 7). CBProd increased for about 30 years in all scenarios, after which it remained stable at those cutting level, which could be maintained. The total 90-year CBProd was clearly positive in all scenarios.

3.3 Biodiversity indicators

The area of old forest increased in all scenarios, most at low cutting level (Fig. 8). In S60, the area increased from the initial 23,400 ha (all in northern Finland) to 1,315,300 ha (89% in northern Finland). In S60, the area of mature forest increased from 1.6 million ha to 10.7 million ha. In SUS and S80 the largest area of mature forest was reached in the middle of the simulation period whereas in S40 and S60 the area increased for the whole 90-year period. In S60, the volume of deciduous trees increased by 33% during the 90-year study period. In SUS and S80, the final volume of deciduous trees was lower than the initial value (391 million m^3).

Figure 8.

The amount of dead wood was clearly higher in scenarios with low cutting targets, especially at the end of the simulation period and for the larger diameter classes (Fig. 9). While the increase of the dry mass of dead wood was constant in S40 and S60, the increase stopped in S80 after 60 years. At the end of the 90-year study period, it was 0.22 Mg ha^{-1} in S80, which is 60% less than in S60. The share of large-sized deadwood (dbh > 30 cm) was about 25% in S60 and 8% in S80. The share of spruce of the total dead wood increased with increasing cutting volume. The share of dead aspen ranged from 1.3% (S80) to 2.3% (SUS).

Figure 9.

4. Discussion and conclusions

4.1 Timber production

This study analyzed the effects of cutting level on timber production, growing stock volume, carbon balance and biodiversity indicators in Finnish forests. To our knowledge, this is the first study to examine the total carbon balance of forestry in Finland, considering all carbon pools mentioned in the IPCC guidelines (2000). The effect of cutting drain on biodiversity indicators has not been studied either at the country level in Finland.

Due to differences in methods, datasets and analyzed scenarios, the outcomes of previous studies (Kärkkäinen et al. 2008; Matala et al. 2009; Hynynen et al. 2015; LUKE 2015) are not fully comparable to ours. Similarly to Hynynen et al. (2015) and LUKE (2015), our study had the requirement of non-declining growing stock volume, while Kärkkäinen et al. (2008) and Matala et al. (2009) aimed at maximal NPV with non-decreasing flow of harvested timber.

In our study the cutting targets were fully met for the whole 90–year period in S40, S60, and SUS (annual cutting volume 73 million m^3) at the country level, and also in S80 in northern Finland. Our S60 can be compared to the LUKE (2015) scenario, representing the annual cutting volumes of 2011–2013. Hynynen et al. (2015) used slightly lower cutting targets than our S60 in their business-as-usual scenario. Despite this, their growing stock volume after 90 years was about 20% lower than in our study. Our S80 was quite similar with another scenario of Hynynen et al. (2015), which had a higher cutting drain.

The annual cutting volume without any decrease in standing log- and pulpwood volume during 90 years was found to be 73 million m^3 yr^{-1}. This is in line with Kärkkäinen et al. (2008) where the sustainable drain was estimated to be 70-78 million m^3 yr^{-1} over 50 years. The annual cutting volumes of saw log (17.5 million m^3) and pulpwood (15.3 million m^3) of our S80 scenario were similar for southern Finland as the LUKE (2015) predictions for the maximum sustainable round wood harvest for 30 years.

The annual volume increments reported in this study (86.6 million m^3 in 2016) are not fully comparable to other studies (e.g. with the 96.2 million m^3 yr^{-1} in commercial forests reported in the Finnish Statistical Yearbook of Forestry (2014)). In our study, the volume of mortality was not included in the increment, leading to 5–6 million m^3 reduction in annual volume increment. The highest average volume increment was achieved in S40, but its difference to S60 and SUS was already small at the end of 90 years simulation period. This suggests that continuously low cutting level will eventually decrease timber supply (Lappi 2016). The total 90-year timber production was the highest in S60.

In our study, the volume of standing timber started to decline in southern and central Finland when the annual harvest was 80 mill. m^3 or more. This decline could be counteracted by using forest fertilization and ditch network maintenance (see e.g., Hedwall et al. 2014; Hökkä et al. 2012; Hynynen et al. 2015; Nilsen 2001; Saarsalmi and Mälkönen 2001). We did not use these treatments but expected a slight growth improvement in artificial regeneration.

Modifying or enlarging the palette of silvicultural practices may also enhance the productivity of Finnish forests. On the other hand, forest landowners most probably select stands for cutting in a less-optimal order than assumed in the calculations of this study. Some landowners do not sell timber at all, while others sell earlier than what would be optimal from the production or profitability point of view. This will have a negative influence on the timber supply of Finnish forests.

We also ignored the effect of climate warming, which most probably increases the growth of most Finnish forests. However, increasing drought may act to opposite direction in southern Finland, and especially at sites with low water holding capacity (see e.g., Kellomäki et al. 2008). Various risks to forests (e.g., wind storms, snow loads, forest fires, drought, pests and pathogens) may also increase in a warming climate, which may decrease the positive influences of climate change (see e.g., Lehtonen et al. 2016; Kellomäki et al. 2008; Peltola et al. 2010; Subramanian et al. 2016; Thom and Seidl 2016).

The share of spruce of harvested volume increased in our study, particularly in scenarios with higher cutting targets, which is related to the large area of established new spruce plantations on fertile sites. Unfortunately, the higher share of spruce might lead to larger risk of biotic (e.g., bark beetles such as *Ips typographus*) and abiotic damages (e.g., wind damages) (see e.g., Peltola et al. 2010; Subramanian et al. 2016; Thom and Seidl 2016).

At the national level, the optimal strategy for timber production may be to implement different scenarios in different parts of the country, or relax the even-flow constraints (e.g., increase the cutting volume gradually for a few decades). Furthermore, there may be a need to consider future changes in the demand for different timber assortments. For example, the demand for pine and spruce pulpwood can be expected to increase more than that of other assortments based on the ongoing investments of forestry industries.

4.2 Carbon sequestration

Sievänen et al. (2014, 2016) have previously calculated the carbon balance of forestry at the national level, considering mineral soils and peatlands. However, their study did not consider changes in the product pools. Hynynen et al. (2015) and Matala et al. (2009) reported result on carbon stock but not on carbon balance. Recent studies by Pukkala (2014 2016), Zubizarreta-Gerendiain et al. (2016) and Lundmark et al. (2016) analysed the carbon balance of forestry, but only at a forest holding or stand level. The common finding of most previous studies is that forests act as carbon sinks, especially at the present cutting rate, but also after a moderate increase in harvested volume. In the current study, forestry was found to be carbon sink at cutting annual levels of 40–80 mill. m^3. The total cumulative carbon balance of forestry was the highest with low cutting levels. This is in line with the results of Sievänen et al. (2016).

The carbon balance of forest soil (CBSoil) had a positive peak in the beginning of the 90-year simulation period. Tending of large areas young seedling and sapling stands, which produced plenty of forest residues (input to soil carbon pool), most probably caused this result. In our simulation, all dense (unmanaged) young stands were tended during the first 10-year period, 287,000 ha in total in S60. This was almost twice as much as the realized 152,000 ha in 2013

(Finnish Statistical Yearbook of Forestry 2014). This is also the likely reason for the slight decrease in volume increment at the beginning of the simulation period, as fast-growing broadleaf seedlings and saplings were removed.

4.3. Biodiversity

The amount of dead wood varied strongly between scenarios, and was about 87% lower in S80 compared to S40 at the end of the 90-year simulation period. The ending deadwood volume was about 5.0 m^3 ha^{-1} in S40 and 2.0 m^3 ha^{-1} in S60. In NFI9 the amount of dead wood was estimated to be 4.2 m^3 ha^{-1} in commercial forests (Korhonen et al. 2013). The share of dead wood of deciduous species, especially aspen, decreased considerably when the cutting level was high. This problem can be alleviated, for example, by prioritizing aspen in the choice of retention trees.

4.4 Conclusions

This study showed that the maximum sustainable annual cutting level of round wood is about 73 million m^3 if forest fertilization, ditch network maintenance and improved regeneration stock are not used more than now. The annual volume increment increased for several decades when cuttings were less than the current volume increment, which led also to increased long-term timber production. Our results suggest that the cutting drain may be gradually increased from the level of 60 million m^3 yr^{-1} in forthcoming few decades. Therefore, cutting less than the current volume increment does not result in timber production losses during the coming decades. The difference should not be either interpreted as “unused cutting potential”.

The total carbon balance of forestry during the 90-year simulation period was the higher, the lower was the cutting target. However, in a very long-term, the total carbon balance is maximized with forest structures that maximize volume increment and cuttings that maintain these structures. The expected use of wood for different product categories, along with expected substitution rates and manufacturing carbon releases (e.g., mechanical pulping) also affect carbon balance. For example, new wood-based products with high substitution rates and low manufacturing releases would increase the total carbon balance. Low cutting level leads led to the highest values of biodiversity indicators.

To conclude, the results of this study showed that an increase of the cutting drain from its current level will decrease timber production, carbon balance and biodiversity of Finnish forestry during the coming 90-year period. In the long-term, a gradual increase in the cutting level to the level of annual net volume increment may be beneficial for the timber production and carbon sequestration. However, this would not be an optimal solution for the amount of dead wood and the area of old forest. Future studies should analyze the influence of intensifying silvicultural practices and warming climate on the development of timber production, growing stock, carbon balance and biodiversity indicators in Finnish forests.

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Table 1.

Variables describing the regions in timber production used in calculations (2016).

	Southern Finland	Central Finland	Northern Finland	Whole of Finland
Area, mill. ha	5.62	5.39	8.38	19.39
Area one sample plot represents, ha	2974	3869	5977	4139
Sample plots, no.	1890	1393	1402	4685
Growing stock, million m^3	816	655	575	2046
Saw log volume, million m^3	316	211	99	626
Pulpwood volume, million m^3	500	444	476	1420
Pine volume, million m^3	337	315	371	1023
Spruce volume, million m^3	312	214	105	631
Birch volume, million m^3	167	126	99	392

Table 2.

Prices (€/m^3), top diameters (cm) and piece lengths (m) of timber assortments for the main tree species used in scenario analysis in different parts of Finland.

	Southern Finland		Central Finland		Northern Finland		Whole Finland	
	Stumpage	Road side	Stumpage	Road side	Stumpage	Road side	Top diameter	Piece length
Pine saw log	55	58	53	55	48	54	16	4.3
Pine pulpwood	15	29	15	28	16	25	6	2.7
Spruce saw log	55	56	53	54	48	53	17	4.3
Spruce pulpwood	17	30	16	29	15	26	6	2.7
Birch saw log	42	49	40	45	40	42	18	3.7
Birch pulpwood	15	29	15	29	15	28	6	2.7
Energy wood	2	20	2	20	2	20	3	2.0

Table 3.

Partitioning of timber assortments into different end-product categories.

	Sawn wood and plywood	Mechanical pulp and paper	Chemical pulp and paper	Biofuel
Pine saw log	0.44	0.00	0.20	0.36
Pine pulpwood	0.00	0.00	0.46	0.54
Spruce saw log	0.44	0.20	0.12	0.24
Spruce pulpwood	0.00	0.50	0.20	0.30
Birch saw log	0.33	0.00	0.30	0.37
Birch pulpwood	0.00	0.00	0.45	0.55

Table 4.

Decomposition rate, manufacturing release, substitution rate, and reuse rate for different end-product categories (tC/tC).

	Sawn wood and plywood	Mechanical pulp and paper	Chemical pulp and paper	Biofuel
Decomposition rate	0.020	0.100	0.100	0.300
Manufacturing release	0.032	0.480	0.130	0.050
Substitution rate	1.000	0.000	0.000	0.800
Reuse rate as biofuel	0.800	0.400	0.400	0.000

Table 5.

Log- and pulpwood cutting targets for 10-year periods under different scenarios, million m^3 yr^{-1}.

		Scenario				
		S40	S60	S80	S100	SUS
	Saw log	7.97	11.96	15.95	19.93	14.55
Southern Finland	Pulpwood	8.77	13.16	17.55	21.93	16.01
	Sum	16.75	25.12	33.49	41.87	30.56
	Saw log	5.24	7.86	10.48	13.09	8.90
Central Finland	Pulpwood	7.64	11.47	15.29	19.11	12.99
	Sum	12.88	19.32	25.76	32.21	21.89
	Saw log	2.39	3.59	4.79	5.98	5.75
Northern Finland	Pulpwood	6.16	9.24	12.32	15.40	14.79
	Sum	8.56	12.83	17.11	21.39	20.36
	Saw log	15.60	23.41	31.21	39.01	29.20
Whole Finland	Pulpwood	22.58	33.87	45.16	56.45	43.79
	Sum	38.18	57.28	76.37	95.46	72.99

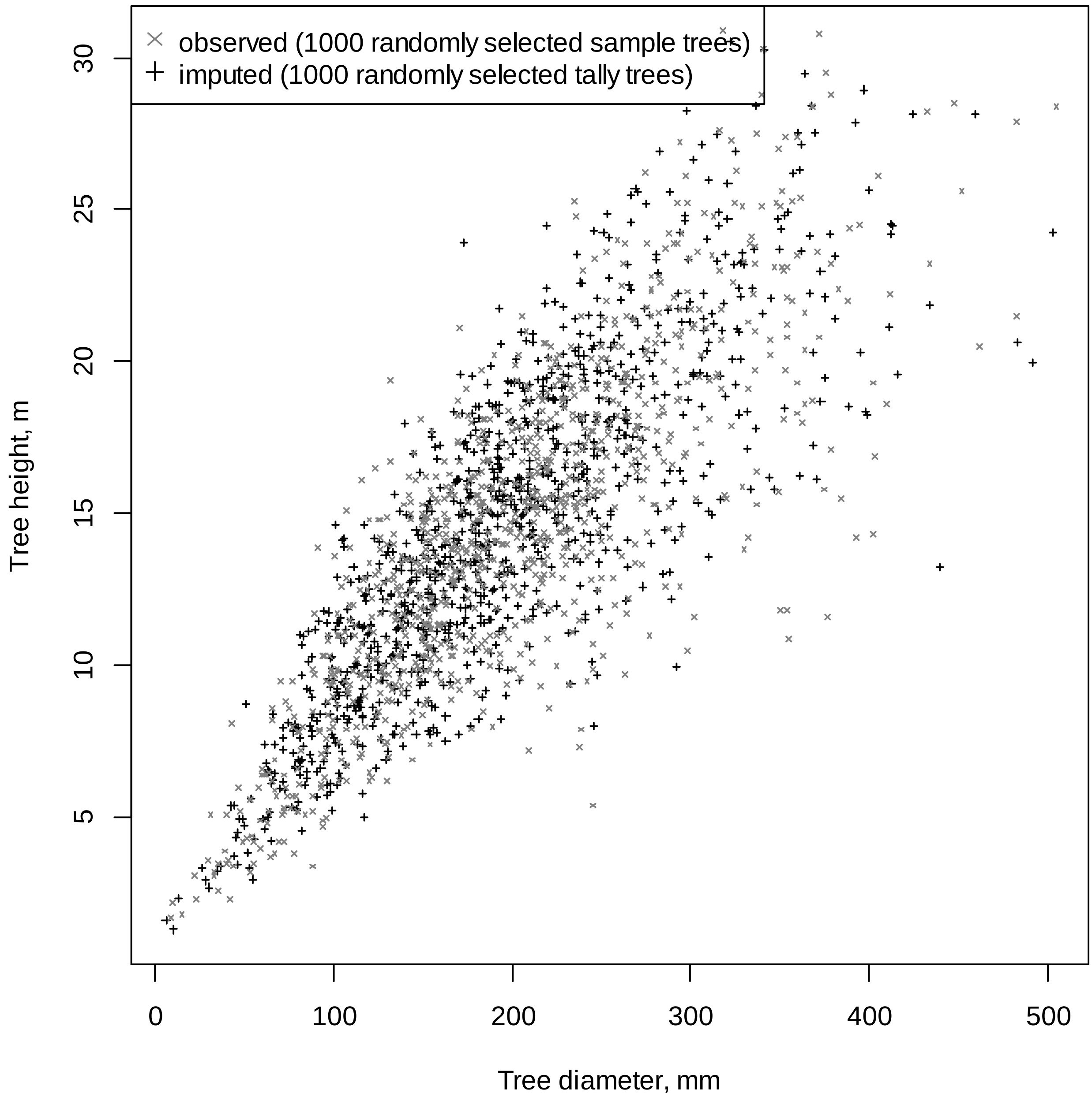

Figure 1. The observed and imputed heights in the Scots pine dataset.

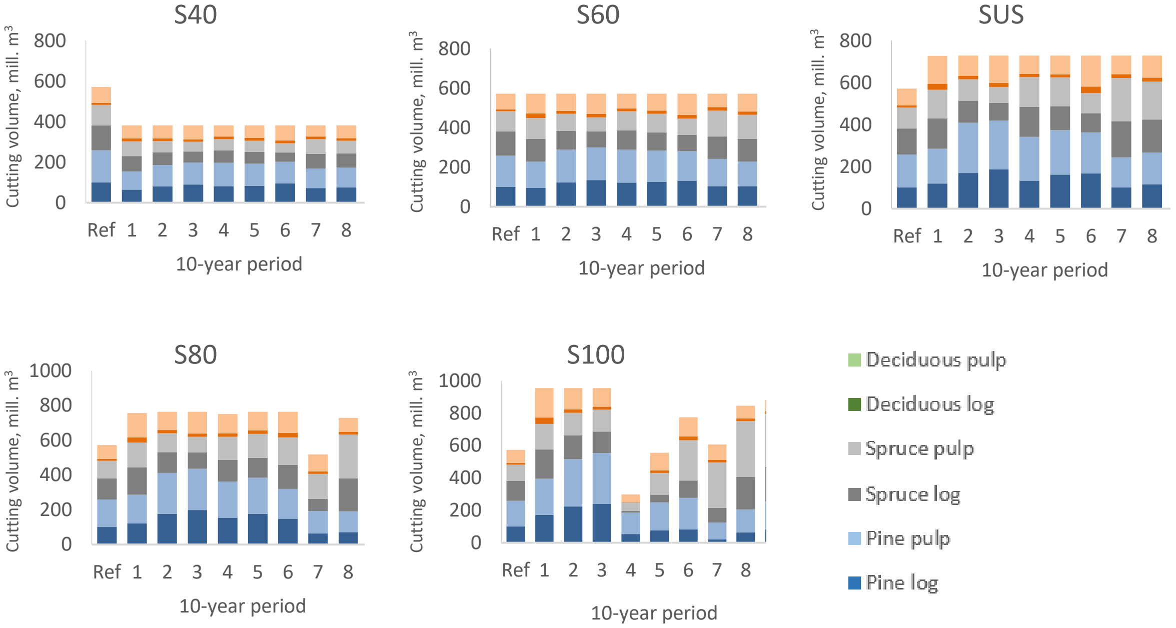

Figure 2. Cutting volume of timber assortments by tree species for cutting scenarios in Finland. Ref = proportions of actual realized cutting volumes during 2004-2013.

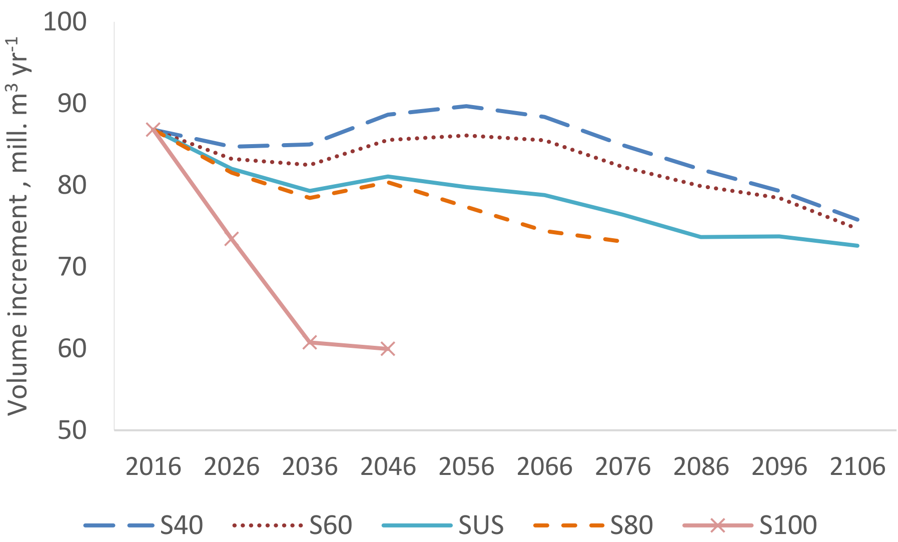

Figure 3. Development of volume increment for cutting scenarios in Finland.

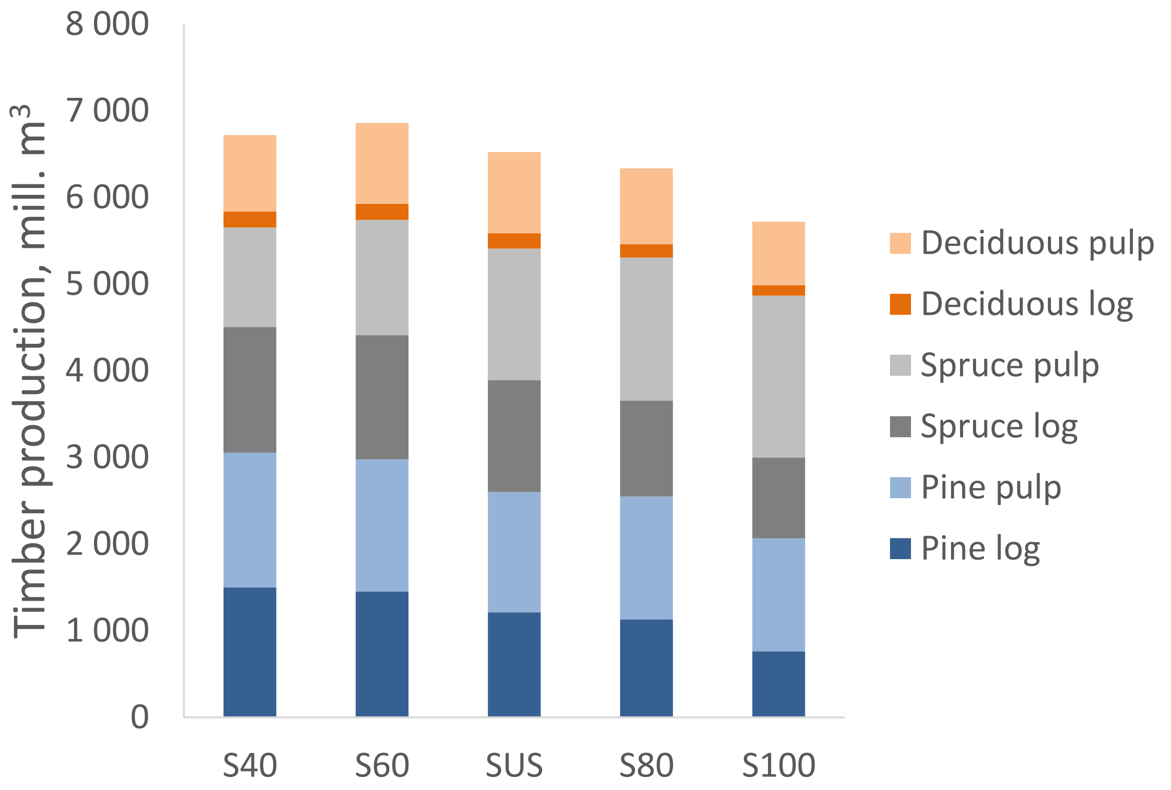

Figure 4. Timber production (TP) in Finland during simulation period. TP = sum of volume increment (final standing volume subtracted with initial standing volume) and harvested volume during simulation period (90 years).

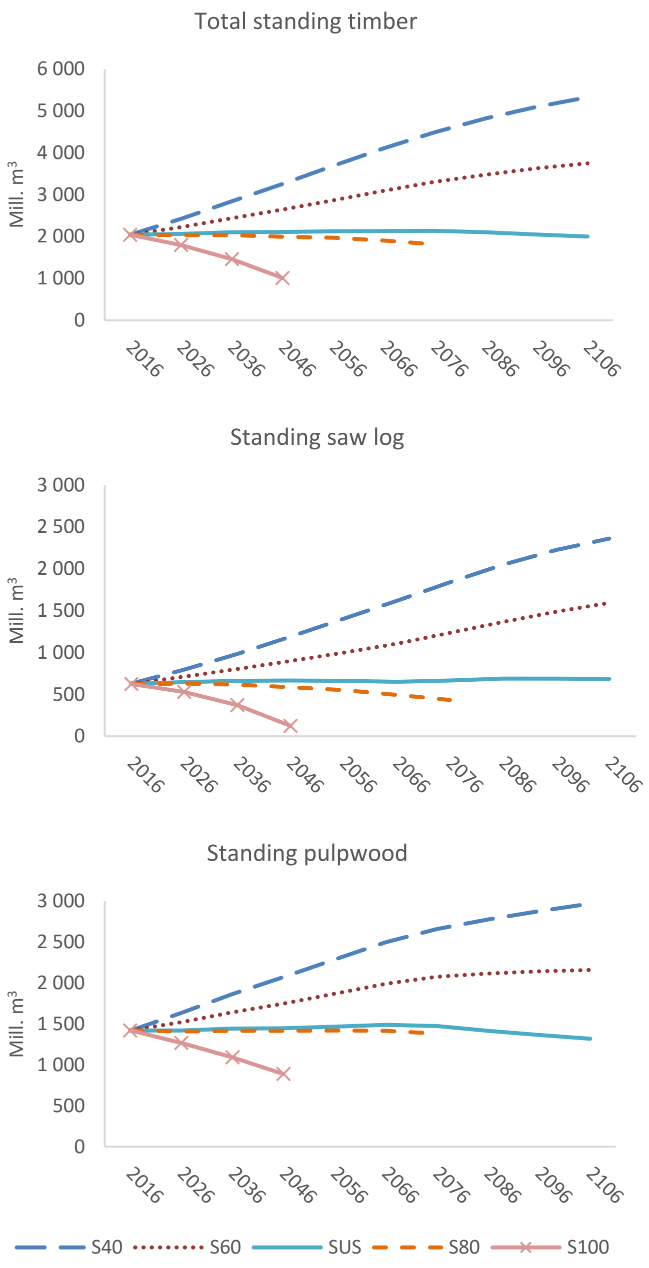

Figure 5. Total standing timber, saw log and pulpwood volume in Finland for cutting scenarios.

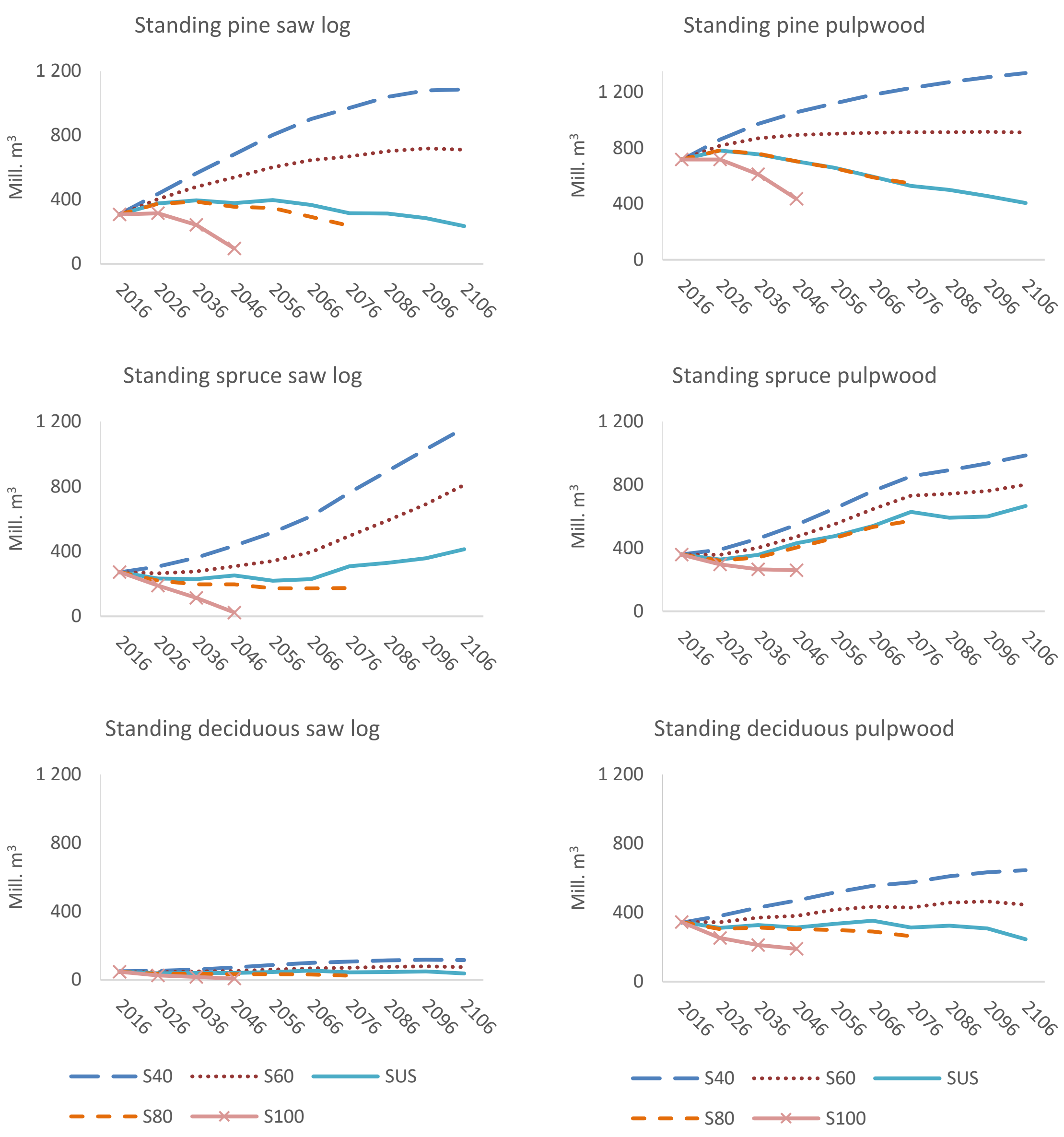

Figure 6. Standing timber volume for timber assortments in Finland by tree species for cutting scenarios.

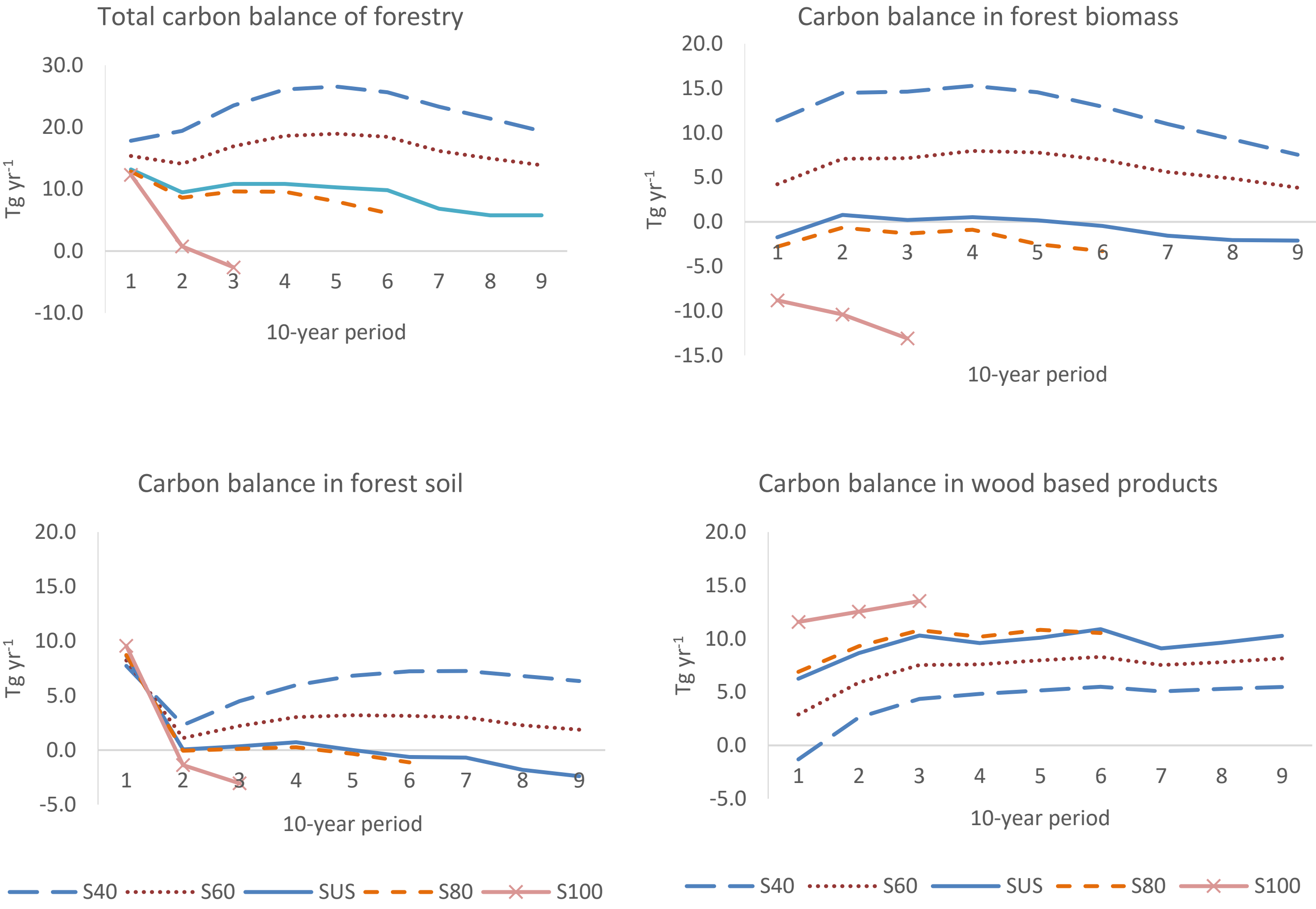

Figure 7. Development of total carbon balance (sequestered – released carbon) and carbon balance of different carbon pools for cutting scenarios in Finland at ten year periods. Positive balance means, that forestry is carbon sink.

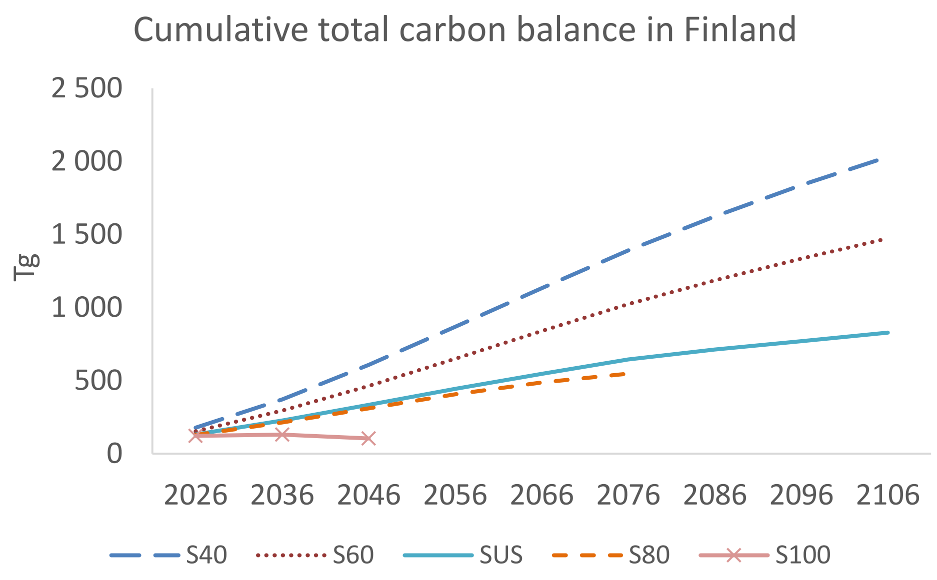

Figure 8. Cumulative total carbon balance in Finland.

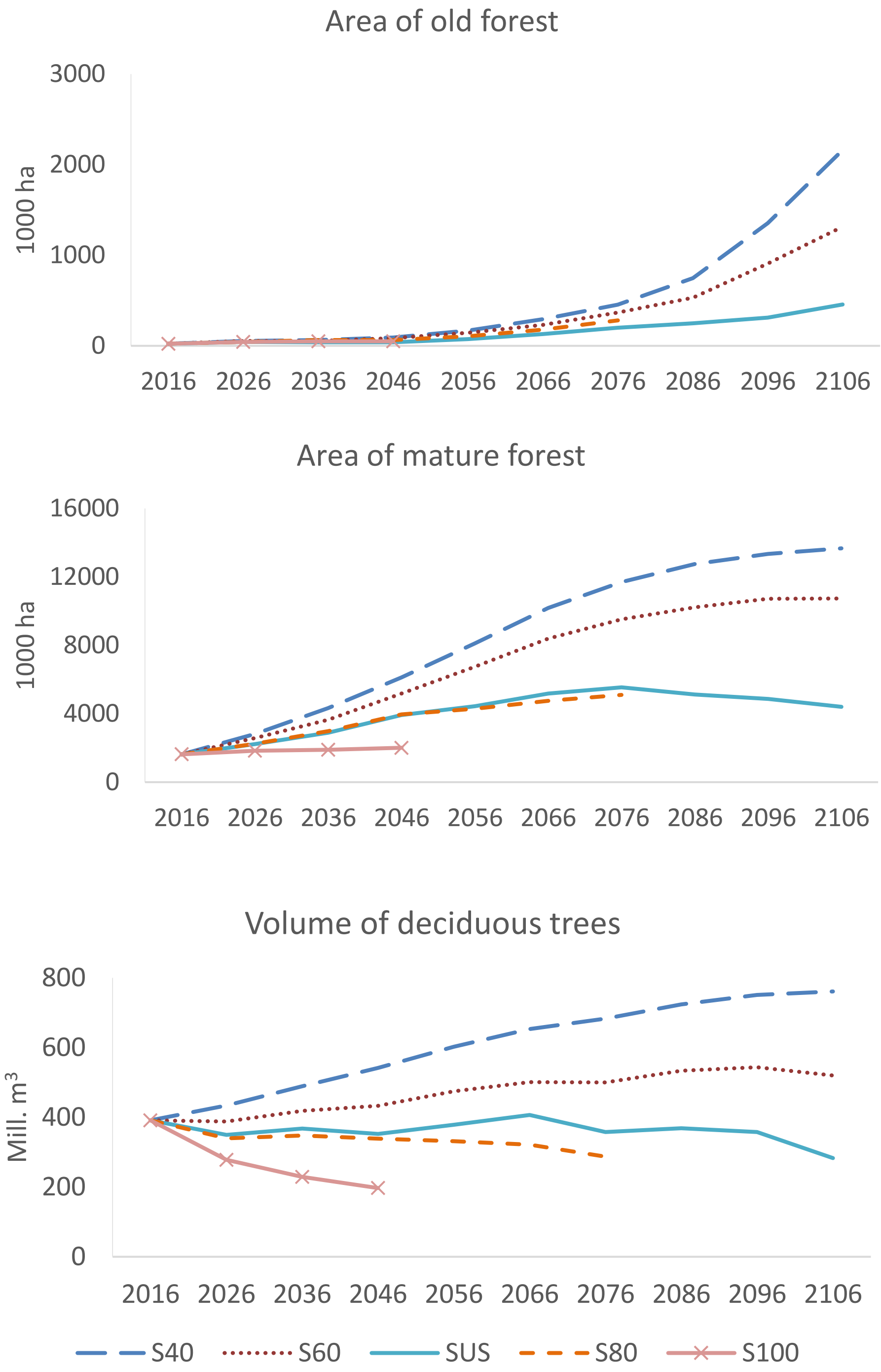

Figure 9. Area of mature and old forests and total volume of deciduous trees in Finland.

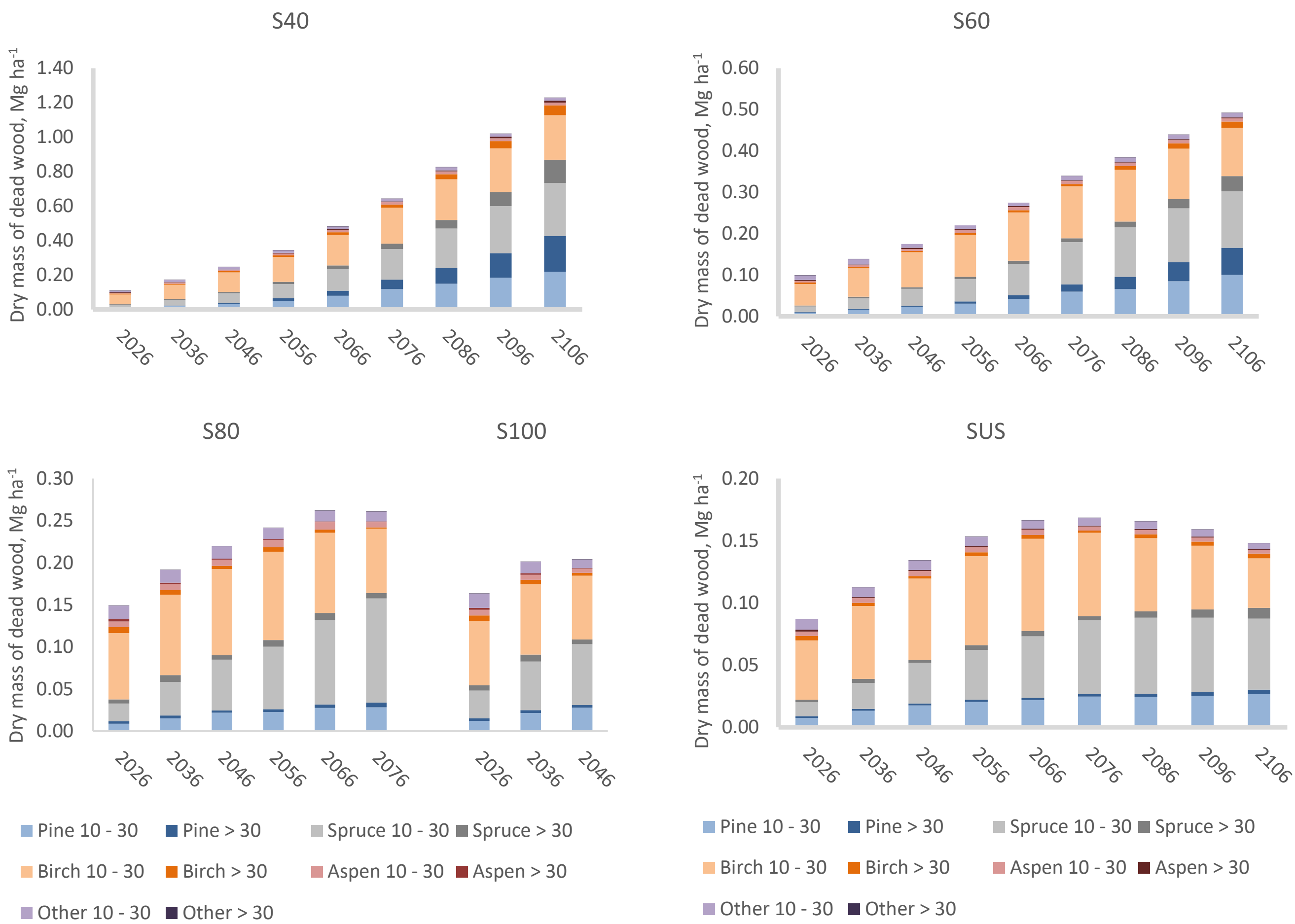

Figure 10. Dry mass of dead wood in Finland for tree species and diameter classes. Note different scales at y-axis.