Scenario analyses on the effects of fertilization, improved regeneration material and ditch network maintenance on timber production of Finnish forests

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Abstract

We used national scenario analyses to examine the effects of fertilization, use of improved regeneration material and ditch network maintenance (DNM), both separately and simultaneously, on timber production of Finnish forests under the current climate. We also analyzed how the area of artificial regeneration, forest fertilization, and DNM developed in different management and harvesting intensity scenarios. The initial data were obtained from the 11th National Forest Inventory of Finland, excluding protected forests. Four sets of even-flow harvesting scenarios with annual timber harvest targets of 60, 70, 80, and 90 million m^3 were developed for 90-year simulation period. Use of improved material in artificial forest regeneration was assumed to result in 10% higher diameter and height increment compared to naturally regenerated seedlings. Sub-xeric pine-dominated and mesic spruce-dominated sites were fertilized, and 40% of drained peatlands were maintenance ditched when they fulfilled a set of pre-determined criteria for temperature sum, stand basal area and mean tree diameter. As a result, when fertilization, improved regeneration material, and DNM were all used, the mean annual volume increment over the 90-year simulation period increased by 3.4–5.4 million m^3 depending on harvesting intensity. The maximum sustainable harvest of timber would be almost 80 million m^3 yr^{-1}. The simulated fertilization area was about four times larger than the presently fertilized area and the simulated DNM area was about the same as the current. Fertilization gave the largest additional 90-year volume increment and the DNM the smallest when they were used separately. The use of improved regeneration material gave the largest additional volume increment in southern Finland and fertilization in central and northern Finland.

Keywords: Even-flow harvesting targets, National Forest Inventory, Tree breeding gain, Volume increment

1. **Introduction**

The volume and volume increment of Finnish forests have increased in recent decades (Finnish Statistical Yearbook of Forestry 2014). In 2004–2013 the average annual round wood harvest was 60 million m^3 (Finnish Statistical Yearbook of Forestry 2014). According to the most recent calculations by Heinonen et al. (2017), the current annual net increment of round wood volume is 86 million m^3 on forested land assigned to timber production (19.3 million hectares). As a comparison, the annual even-flow round wood harvest, which does not decrease the growing stock volume during the coming 90-years, is 73 million m^3 (Heinonen et al. 2017). Despite increased volume growth, there is a pressure to increase the timber production of Finnish forests even further to face the wood demand of the growing forest based bioeconomy sector. Increasing volume increment also helps to meet the climate change mitigation goals set by the European Union (The Finnish Bioeconomy Strategy 2014). Use of improved regeneration material (breeding gain), forest fertilization and ditch network maintenance (DNM) on drained peatlands have been proposed as means to increase the timber production of Finnish forests (e.g., Hökkä 1997; Saarsalmi and Mälkönen 2001; Ruotsalainen 2014; Haapanen et al. 2016; Hökkä et al. 2017).

In Finland, the average annual forest regeneration area was ca. 125,000 hectares during 2009–2013. Of this area, 65% of was planted with Norway spruce (*Picea abies*), Scots pine (*Pinus* *sylvestris*), and silver birch (*Betula pendula*) seedlings, 20% was seeded by Scots pine and 15% was naturally regenerated using mainly seed tree cutting in Scots pine stands (Finnish Statistical Yearbook of Forestry 2014). Currently, the share of Norway spruce of the total planting area is high, ca. 70%. In the early 1990s, it was only 25–30%. The increasing use of Norway spruce seedlings in regeneration is partly due to the high risk of moose browsing and other mammal damages in young Scots pine and birch stands (Finnish Statistical Yearbook of Forestry 2014).

Use of improved material in artificial regeneration is expected to enhance the forest growth in the long run due to the obtained breeding gain. In Finland, the mean annual volume production of the 1st and 1.5-generation Scots pine seed orchard stocks has been 7–24% higher than that of unimproved stock (Haapanen and Mikola 2008; Haapanen et al. 2016). In Sweden, seeds from the 1st generation Norway spruce and Scots pine seed orchards of untested plus trees have had 10–15% higher volume production than unimproved seed stocks (Rosvall et al. 2001; 2002). The use of improved seeds and seedlings in forest regeneration may gradually provide also significant economic benefits due to enhanced growth rates of trees, despite the higher price of improved material (Ahtikoski et al. 2012a; 2013). However, lack of regeneration material with high breeding gain currently constraints the use of improved regeneration material in Finland, especially in Norway spruce (Finnish Statistical Yearbook of Forestry 2014).

During 2009-2013, the total average annual area of growth fertilization (used to improve growth) and remedial fertilization (used to improve nutrient-balance of soil) was about 43 000 ha, of which fertilization of upland forests accounts for 70% (Finnish Statistical Yearbook of Forestry 2014). Nitrogen (N) is the main growth-limiting nutrient in many boreal upland forests (Saarsalmi and Mälkönen 2001; Hedwall at al. 2014). In Finland, N fertilization has increased the volume growth in Norway spruce on mesic sites and in Scots pine on sub-xeric sites up to 22–36% (Kukkola and Saramäki 1983; Mälkönen and Kukkola 1991). The effect of N fertilization continues for about 7 years in Scots pine and about 10 years in Norway spruce (Laakkonen et al. 1983). Repeated N fertilization has increased the volume growth in Norway spruce stands by 56–81% in northern Finland (Smolander et al. 2000), and in Scots pine stands up to 25% in Sweden (Berg et al. 2014).

Middle-aged stands with good volume increment usually give the best growth response to fertilization (Gustavsen and Lipas 1975). The greatest economic benefits from N fertilization have been obtained in stands where the value increment of trees (transition from pulpwood to saw logs) is considerable (Laakkonen 1994; Pukkala 2017a). Other fertilizers, like wood ash, phosphorus (P) and potassium (K) are used especially on N-rich drained boreal peatlands (e.g., Nilsen 2001; Moilanen et al. 2005; Hökkä et al. 2012). In Finland, PK fertilization has resulted in good long-term growth responses on drained peatlands (Hökkä et al. 2012).

The annual DNM area of Finland was about 60,000 hectares during 2009–2013 (Finnish Statistical Yearbook of Forestry 2014). DNM has been implemented mainly on drained peatland sites where the gradual deterioration of ditches reduces their water transportation capacity. Maintaining the drainage function of ditches improves or maintains tree growth by lowering the water table level (Paavilainen and Päivänen 1995). In Finland, DNM has resulted in positive long-term growth responses in field experiments (increases of up to 1.1 m^3 $ha^{–1}$ yr^{-1} for 15–20 years) (Ahti 2005, Ahti et al. 2008) and in model simulations (up to 1.8 m^3 $ha^{–1}$ $yr^{–1}$) (Hökkä 1997).

Scenario analysis can be used to study the effects of different forest management methods on forest development. A scenario can be considered as a vision of the future, or a projected sequence of predefined events, which can be constructed, for instance with simulation and optimization techniques. In the study of Hynynen et al. (2015), scenario analyses were used to assess the effects of forest management intensification methods on forest growth at the national level in Finland. The harvest level was a consequence of the used strategy, resulting in temporal variation in annual removals. Hynynen et al. (2015) used different management intensification methods, such as fertilization, DNM and use of improved regeneration material, but they did not analyze their effects separately. They used data from the 9th and 10th Finnish National Forest Inventories (NFI9 and NFI10) (Korhonen et al. 2007; Tomppo et al. 2011).

In this study, we used national scenario analyses and the latest NFI data (NFI11) to estimate the effects of N fertilization, improved regeneration material, and DNM, both separately and simultaneously, on timber production of Finnish forests under the current climate. Each management intensification method was evaluated at four different levels of annual round wood harvest: 60, 70, 80, and 90 million m^3. We also studied how the different scenarios (i.e., combinations of the management and harvesting intensity levels) affected the areas of artificial regeneration, fertilization, and DNM, and compared them to the corresponding areas of past years. We used simulation and optimization to construct scenarios for 90 years.

2. **Material and methods**

2.1 Forest data used in analyses

Forest data used in this study was a sub-sample of the sample plots of the 11th National Forest Inventory (NFI11) of Finland, which was conducted between 2009 and 2013 (Korhonen

2016). The NFI data are collected from a systematic network of clusters of sample plots covering whole Finland. For this study, only one sample plot (number 3) was selected from every cluster on forest land assigned to timber production. Compared to the results of the latest national forest inventory (all NFI11 plots), the area of herb-rich and mesic sites in our sample was 1.4% higher and the area of sub-xeric sites was 6.7% lower. The total growing stock volume of Scots pine, Norway spruce, and deciduous trees were 2.6, 1.7 and 9.8% lower than in the whole data. The area of young thinning stands was 4.0% higher and the area of advanced thinning stands 3.8% lower than in the whole NFI11 data. In addition, the area of mature stands was 9.5% lower.

Our dataset included 1890, 1393 and 1402 sample plots from southern, central and northern Finland, respectively (Table 1). The division was based on earlier-applied forestry center areas of southern (1–6), central (7–10) and northern Finland (11–13) (see Finnish Statistical Yearbook of Forestry 2014). Analyses were done separately for these three regions, and the country level results were combined from regional results. In total, 1070 plots (4.36 million hectares) of 4685 plots were located on drained peatlands.

Table 1.

In NFI trees are inventoried by crown classes to take into account both large and small trees. Trees belonging to the plot are selected with an angle gauge (relascope). A sample plot included nine trees on the average in our data. Variables recorded for sample trees were tree species, diameter at breast height (dbh, cm) and tree height (m). The number of trees per hectare that each measured tree represented was calculated from dbh and the used basal area factor. Height was measured for every 7th sample tree. For this study, the missing heights for trees larger than 8 cm in dbh (46473 trees) were imputed using a nonlinear mixed-effects model (Mehtätalo et al. 2015) based on the Näslund's (1937) function (see Heinonen et al. 2017 for details).

2.2 Models used in scenario analyses

The Monsu software (Pukkala 2011) was used to produce the scenarios. The software has been used earlier in several studies to simulate tree growth and forest management, and to optimize management (e.g. Kurttila et al. 2002; Hurme et al. 2007; Pukkala et al. 2009; Heinonen et al. 2017). Diameter growth, survival, and ingrowth of trees were predicted with the models of Pukkala et al. (2013) and height growth with the model of Pukkala et al. (2009). These models were used because they are suitable for all stand structures. In addition, they can predict the gradual appearance of advance regeneration, which was regarded important for realistic long-term predictions of the development of forest resources.

The same growth models were used for upland forests (mineral soils) and drained peatlands. In drained peatlands, drainage class (available in the inventory data) was used to make downward corrections for growth prediction for all sites except those classified as well-drained. The taper functions of Laasasenaho (1982) were used to calculate the assortment volumes in logging. Quality deductions were made based on Mehtätalo (2002) and Malinen et al. (2007) as explained in Pukkala et al. (2014a).

To include the latest information on the growth of Finnish forests, the diameter increment models of Pukkala et al. (2013) were calibrated based on the growth measurements of NFI11 as follows. First, the predictions of the so-called MELA models (Hynynen et al. 2002; MELA2012 Reference ... 2013) implemented in Monsu were calibrated. This was done based on the calculations made by Natural Resources Institute Finland on the changes in basal area growth between the latest national forest inventories (MELA 2015). Secondly, the models of

Pukkala et al. (2013) were calibrated separately for different tree species and geographical regions so that the current annual net increment in growing stock volume at the regional level was the same as obtained with calibrated MELA models (Hynynen et al. 2002, MELA2012 Reference ... 2013; see Heinonen et al. 2017 for details).

2.3 Simulation of treatment schedules for plots

Tree data were imported to Monsu as tree lists. The simulation horizon was set to 90 years, divided into nine 10-year periods. The stand development of each sample plot was simulated according to pre-defined management schedules. The schedules included cuttings and other treatments. The basic rules for the simulation of treatment schedules were the same for all scenarios. The use of breeding, fertilization or DNM affected the schedules by altering the growth rate of trees. In all scenarios, the currently recommended basal area threshold for thinning and the diameter (dbh) threshold for final felling were multiplied by 0.9 to define the earliest possible timing for thinnings and final felling (Äijälä et al. 2014). The purpose of this was to add flexibility to the timing of harvests. Additional treatment schedules with postponed cuttings and a schedule without any cutting were also simulated for each sample plot. These rules led to the simulation of all reasonable cutting alternatives that represented the current forest management practices. Thinnings were simulated as uniform thinning corresponding to the current trend towards using more thinning from above, in which trees are cut mainly from the upper crown classes. Regeneration treatments were simulated immediately after clear cutting.

2.4 Management intensification methods

2.4.1 Use of improved regeneration material

Improved regeneration material was used only on upland forest sites. Planting of Norway spruce was always simulated on mesic and herb-rich upland forest sites (about 50% of total data area) while silver birch was planted only on mesotrophic herb rich upland forest sites (2%). Sowing of Scots pine was used on sub-xeric upland forest sites (20%) and natural regeneration on poorer upland forest sites and on all peatland sites (28%). This meant that 72% (13.2 million hectares) of the total area examined was potentially available for the use of improved regeneration material at some point during 90 years. In scenarios where the improved seeds and seedlings were used, they were used in every artificial regeneration area. The genetic growth gain was assumed to be 10%, which corresponds to observed genetic gains of the 1st generation seed orchards with untested plus trees in Finland (Haapanen and Mikola 2008; Haapanen et al. 2016). The gain was simulated by multiplying the predicted diameter and height increments by 1.1 in the growth models. Seedlings of different tree species were also expected to regenerate naturally, and their growth predictions were kept on the basic level. Tending treatments for dense seedling and sapling stands were simulated according to the current management recommendations for private forests in Finland (Äijälä et al. 2014).

2.4.2 Nitrogen fertilization

The models of Kukkola and Saramäki (1983) were used to predict the response of volume growth to nitrogen (N) fertilization on upland forest sites. These models are based on a high number of long-term growth measurements in several fertilization experiments located in different parts of Finland (Kukkola and Saramäki 1983). The inventoried plots (478 plots in total) represent different age classes of forests, and the development of each plot was monitored for 9–19 years.

The models of Kukkola and Saramäki (1983) consists of two sub-models

$$\Delta I_t = \mathrm{A}_t \times \mathrm{B} \tag{1}$$

$$\mathrm{A}_t = \mathrm{f}\ (t, N, P, T) \tag{2}$$

$$B = f(Fre, Hdom) \times f(SI) \tag{3}$$

where ΔI_t is the increase in volume growth t years after fertilization (m^3 ha^{-1}), A_t is the effect of time and the amount and type of fertilizer and B is the effect of site and growing stock. N is the amount of added nitrogen (kg ha^{-1}), T is the type of fertilizer and P indicates whether the fertilizer also includes phosphorus. Fre is the number of trees per hectare, $Hdom$ is the dominant height of the stand at the time of fertilization (m) and SI is the site index (dominant height at the stand age of 100 years, m). These models have been developed separately for Scots pine and Norway spruce stands. Predictions can be calculated for three types of fertilizers: urea, ammonium sulfate and ammonium nitrate with lime. In this study, the fertilizer type was assumed to contain 25% of N and 2% of phosphorus. Furthermore, 50% of N was in the form of ammonium sulfate and the other 50% of N was in the form of nitrate. The used N dose was 150 kg ha^{-1}, which means that 600 kg of fertilizer was used per hectare (see examples of calculated responses in Figure 1a).

Figure 1

To investigate the relationship between additional volume increment (obtained from the response model of Kukkola and Saramäki (1983)) and additional diameter increment (required in simulation), the growth of several Scots pine and Norway spruce stands on different sites were simulated using individual-tree growth models (Pukkala et al. 2013). The results were used to calculate growth multipliers for stem volume and mean tree diameter. The multipliers were obtained by comparing the predicted growths of similar growing stocks on different sites. The following relationship was found between diameter growth and volume growth multipliers:

$$\text{Diameter growth multiplier} = (\text{Volume growth multiplier})^{0.9}$$

The models of Kukkola and Saramäki (1983) give the response separately for different years. In the current study, growth was simulated in 5-years steps. When calculating the response, the 3rd year since fertilization was used for the first 5-year period, the 8th year for the second 5-year period etc. This simplification gave approximately same total response as the response calculated separately for each year.

In scenarios where fertilization was used, it was simulated only for sub-xeric sites dominated by Scots pine and for mesic sites dominated by Norway spruce when the following criteria were fulfilled: stand mean diameter 15–30 cm, basal area 5–30 m^2 ha^{-1} and temperature sum 900–1,400 degree days (d.d.) (see Pukkala 2017a). Fertilization and thinning were not simulated during the same 10-year period.

2.4.3 Ditch network maintenance

A tabular model for the stand growth response to DNM treatment on drained peatlands was obtained from the Natural Resources Institute Finland (Hökkä, personal communication). It is based on a high number of growth measurements on permanent sample plots on drained peatland sites (the SINKA plots, a sub-sample of NFI7 plots) in central and northern Finland (Hökkä and Kojola 2003; Ahtikoski et al. 2012b) and other inventory data measured on different thinning (Hökkä and Kojola 2002) and drainage (Ahti and Päivänen 1997) experiments on drained peatland sites throughout Finland.

The model gives the percentage increase in dbh growth for the different types of drained peatland stands based on stand basal area (m^2 ha^{-1}), time since DNM (years), and geographical region (d.d.). For this study, the tabular model was converted to a continuous model, similar to Equation 1, where the first part described the effect of time and the second part the effects of stand basal area and temperature sum. The equation model predicted accurately the behavior of the tabular model of Hökkä (personal communication) (see Figure 1b).

The NFI plots did not include information on whether the stand would benefit from DNM. We wanted to avoid simulation of larger DNM areas than the present, because ditches of poorly growing drained peatlands are not recommended to be maintained in the future due to low economic profitability (Äijälä et al. 2014). Thus, the DNM area may even decrease in the future from the current DNM area. Therefore, we used DNM only for 40% of those drained peatlands fulfilling the given criteria for DNM as follows: the stand mean diameter 8–25 cm, basal area 8–25 m^2 ha^{-1} and temperature sum 900–1,400 d.d.

2.5 Management and harvesting intensity scenarios

Altogether twenty different management and harvesting intensity scenarios were produced to analyse the effects of forest management and harvesting intensity on timber production. The scenarios were named as *Basic*, *Breeding, Fertilization, Ditching* and *All* (Table 2). In the *Basic* scenarios, improved regeneration material, fertilization or DNM were not used. Their effects were analysed separately in the *Breeding*, *Fertilization*, and *Ditching* scenarios and as combined in the *All* scenario.

Each of the above-named scenarios were combined with four different annual even-flow harvesting targets, namely 60, 70, 80, and 90 million m^3. Henceforth, the scenarios are referred to by abbreviations that express both the management intensification method and the harvesting target, e.g., *Basic60* or *Breeding70*.

Table 2

The 60 million m^3 annual harvesting target corresponds to the current annual harvest (Finnish Statistical Yearbook of Forestry 2014). Saw log and pulpwood harvesting targets were derived by summing the realized harvesting volumes of 2004–2013 (Table 2), separately for the three regions. Five million $m^3 yr^{-1}$ was added as a pulpwood-sized energy wood. The rest was assumed to be small-sized household energy wood. For example, the harvesting target of 60 million $m^3 yr^{-1}$ included the following amounts of saw logs, pulpwood, pulpwood sized energy wood and household energy wood: 23.4, 28.9, 5.0 and 2.7 million $m^3 yr^{-1}$, respectively. The harvesting targets of 70, 80, and 90 million $m^3 yr^{-1}$ for saw log and pulpwood were proportional to the harvesting volumes of the 60 million m^3 scenarios. For example, the saw log volume target for 80 million was 33% higher than for 60 million m^3. Harvesting targets were not specified separately for different tree species.

2.6 Problem description and optimization

The best combination of treatment schedules simulated for the NFI sample plots was found by optimization. The objective of the treatment scheduling problem was to maximise simultaneously timber (saw log and pulpwood) production and profitability (net present value) of forest management, with the harvested volume of saw log and pulpwood being equal to the target of each scenario (Table 2). When the harvesting target could not be met during every 10-year period, more importance was given to fulfilling the targets of earlier 10-year periods. This was done to find out for how long it is possible to maintain a certain harvesting level.

A hybrid heuristic method of simulated annealing (SA) (Lockwood and Moore 1992; Dowsland 1993; Öhman and Eriksson 1998) and Hero (Pukkala and Kangas 1993; Pukkala and Heinonen 2006) was used in optimization. This hybrid method has been shown to perform equally well or better in non-spatial optimization problems than using SA alone (Pukkala and Kurttila 2005). In addition, SA has been shown to produce near-optimal solutions in non-spatial problems such as in this study (Bettinger et al. 2002). The Hero heuristic examines systematically all the treatment schedules trying to improve the best solution found by SA, and accepts all schedules that improve the solution. The parameters of the heuristics used in optimization were set separately for every optimization run to find the best possible solution regarding profitability and the timing of harvests. When maximizing the net present value, optimization prefers schedules with high incomes and low costs, especially in the beginning of the simulation period.

Net incomes from cuttings were obtained as a difference between roadside prices of timber assortments (Table 3) and harvesting costs, calculated with the functions of Rummukainen et al. (1995). The discount rate used in calculating net present value was 3%. The same silvicultural costs were assumed in all scenarios and in different parts of Finland (Table 4).

Table 3

Table 4

3. Results

3.1 Area of artificial regeneration, forest fertilization and DNM

The average annual planting and sowing area increased with increasing harvesting targets of scenarios due to the increased area of the final fellings (Figure 2). For example, the planting and sowing area of *Basic60* was only 45% of the average artificial regeneration area of Finland during 2009–2013, but in *Basic80* it was already clearly larger than it has been in recent years. Use of individual management intensification method decreased the area of artificial regeneration, compared to the Basic scenarios, most when fertilization was used. For example, in *Fertil70* the area of artificial regeneration was 9% smaller than in *Basic70* and in *Breeding70* the area was 6% smaller than in *Basic70*.

Figure 2

The average annual fertilization area was the largest in *Fertilization70*, being 128,100 hectares (Figure 3), which was almost four times the average annual fertilization area of upland forests in Finland during 2009–2013. The simulated fertilization area was clearly larger than the fertilized area of recent years in all parts of the country. Higher harvesting targets decreased fertilization area, partly because thinning and fertilization were not allowed during the same 10-year period, and a final felling excluded fertilization for several 10-year periods.

The average annual DNM area was the largest in *All90*, being 40,100 hectares (Figure 3). This was 18,000 hectares smaller than the average annual DNM area of Finland during 2009–2013. Scenarios with 60 million m^3 harvesting target had about 5,000 hectares smaller DNM area than obtained in scenarios with higher harvesting targets.

Figure 3

3.2 Timber production and growing stock volume

The annual harvesting targets of 60 and 70 million m^3 were met in all 10-year periods. The 80 million m^3 harvesting target could not be met during the three latest 10-year periods, not even when all three management intensification methods were used. The 90 million m^3 harvesting target was met only for the three first 10-year periods (Figure 4).

Figure 4

Figure 5 shows the development of growing stock volume during the 90-years simulation period with 70 million m^3 annual harvesting target. In northern Finland, the volume of standing timber increased steadily for the whole simulation period, whereas in the other parts of the country it stayed more or less constant.

Figure 5

Total timber production was calculated based on the change in growing stock volume during the 90-year period (Figure 5) and the volume of harvested trees (Figure 4). The timber production of the whole 90-year simulation period was the highest, 79.2 million m^3 yr^{-1}, for the *All60* scenario, which was 3.4 million m^3 yr^{-1} higher than in *Basic60* (Figure 6). When the annual harvesting target was 70, 80 or 90 million m^3, use of fertilization, DNM, and improved regeneration material increased timber production by 4.1–5.4 million m^3 yr^{-1}. Increasing the annual harvesting target decreased timber production. Timber production was in *Basic70* 1.4 million m^3 yr^{-1} and in *Basic80* 6.2 million m^3 yr^{-1} lower than in *Basic60*. Increasing the annual harvesting target beyond 70 million m^3 decreased timber production significantly, irrespective of the use of management intensification methods.

Figure 6

Compared to *Basic80*, DNM alone increased timber production by 0.2 million m^3 yr^{-1}, while fertilization increased it by 1.9 million m^3 yr^{-1}, and the use of improved regeneration material by 1.7 million m^3 yr^{-1}. However, reducing the harvest by 10 million m^3 yr^{-1}, from 80 to 70 million m^3, improved timber production by 4.8 million m^3 yr^{-1}. The use of fertilization, DNM, and improved regeneration material could not compensate for the negative effect of increasing harvest on timber production. However, the situation was different at lower harvesting levels. Increasing the harvesting from 60 to 70 million m^3 y^{-1} could be easily compensated for by intensified management, which resulted in three times higher increment in timber production (4.4 million m^3) compared to the effect of reducing round wood harvest from 70 to 60 mill m^3y^{-1} (1.4 million m^3).

The benefits of the management intensification methods varied over time. For example, fertilization and DNM produced almost immediate increases in volume production whereas the gains of using improved seeds and seedlings accrued gradually (Figure 7). Fertilization was the most efficient way to increase timber production, resulting in a rather constant increase of 2–3 million m^3 yr^{-1}. DNM was the least beneficial with at most 1 million m^3 yr^{-1} increase in timber production. The use of improved regeneration material increased the timber production gradually and resulted in the mean annual increase of 3.3 million m^3 yr^{-1} over the whole 90-year period when harvesting 70 million m^3 y^{-1}. When the annual harvesting target was 70 million m^3, the use of improved regeneration material was the most influential management intensification method in southern Finland, whereas fertilization was the most influential in other parts of Finland over the whole 90-year period (Figure 8).

Figures 7 and 8

4. Discussion

This study used NFI11 data, simulations with the models of Pukkala et al. (2013), and optimization, to analyze the effects of different management intensification methods on the timber supply of Finnish forests. The NFI data are collected from a systematic network of clusters of sample plots covering whole Finland (Korhonen 2016). Although only one sample plot from every NFI cluster was used in this study and led to smaller solution space in the optimization, the sample plots used in this study are still a representative sample of Finnish forests and their number is large enough for reliable results at the regional level. The models of Pukkala et al. (2013) are also based on over 60,000 growth observations representing different forest structures ranging from uneven-aged to strictly even-aged stands. In addition, the model set also predicts the gradual appearance of advance regeneration, which was regarded important for realistic long-term predictions of the development of forest resources. Since many different stand structures are encountered in Finnish forests and in the NFI data, the models of Pukkala et al. (2013) were considered suitable for our study. We constructed the scenarios with simulation and optimization technique. The simulation and optimization technique used has been validated in many studies where optimization problems have been similar (non-spatial, multiple periods, simple objectives) (e.g. Bettinger et al. 2002; Pukkala and Kurttila 2005; Pukkala 2017b).

Our results showed that the timber supply of Finnish forests cannot be increased drastically by increasing the use of forest fertilization, improved regeneration material, and DNM. The annual harvesting of saw log and pulpwood could be increased by 3.4–5.4 million m^3 when using a realistic combination of forest fertilization, DNM, and improved regeneration material. Our results also suggest that more harvesting could have been allocated to northern forests.

In our study, use of improved regeneration material increased long-term timber production the most in southern Finland while fertilization was the most influential in central and northern Finland. However, if a rapid increase in volume production is required, the use of improved regeneration material is not an efficient option since it will have a significant effect on timber production only after several decades. When N fertilization, DNM, and improved regeneration material are all used simultaneously, the maximum sustainable harvest of saw logs and pulpwood would be almost 80 million m^3 yr^{-1}. However, from the timber production point of view it would be wiser to cut less than 80 million m^3 yr^{-1} and use imported timber to satisfy the total wood demand. If the annual round wood harvest is 70 million m^3, the additional harvest, compared to the present harvest, could be achieved with the use of forest fertilization, DNM and improved regeneration material.

Our main results are in line with the findings by Hynynen et al. (2015), who analysed the long-term effects of similar management intensification methods (only as combined) on the timber supply of Finnish forests. However, in their study the annual clear-cutting area and fertilization area were about 15% higher and the DNM area was 50% higher than in our scenarios with similar harvesting volumes. The smaller clear-cutting area of our scenarios, compared to the intensified forest management scenario of Hynynen et al. (2015), may be partly explained by the use of uniform thinning in our study (instead of thinning from below), which tends to increase rotation length. In addition, we simulated the gradual appearance of advance regeneration, which sometimes led to the removal of the upper canopy instead of final felling. When compared to the "high-quality scenario" of Hynynen et al. (2015), where diverse thinning methods were used more often alongside similar harvested volume, the difference was clearly smaller.

Hynynen et al. (2015) also assumed that the use of improved regeneration material would provide a 7% genetic growth gain based on the results of Haapanen and Mikola (2008). Whereas we assumed slightly higher, 10%, increase in diameter and height increment. No long-term data are available from actual regeneration sites of forestry practice for estimating the tree breeding gain. According to the progeny tests, the use of seeds from orchards of plus trees selected based on the progeny tests may increase the annual volume increment up to 25% compared to the increment of unimproved stock (Rosvall et al. 2002; Berlin et al. 2012). However, the results of progeny tests are not directly applicable to scenario simulations. Natural regeneration also offers possibilities to select the best individuals in tending treatments. In addition, due to mortality and lack of timely management, most artificially regenerated stands will eventually be mixtures of both artificially (planted or seeded) and naturally regenerated seedlings.

Current lack of forest regeneration material having high breeding value also reduces possibilities to benefit from tree breeding gain (Finnish Statistical Yearbook of Forestry 2014). Insufficient supply of improved seedlings will most probably continue especially for Norway spruce for several decades (Himanen 2016) because seed crops of the oldest seed orchards are declining and the area of young orchards is small. The use of too homogenous regeneration material should also be avoided due to increasing silvicultural risks (Sonesson et al. 2001).

The areas of fertilization and DNM were restricted in this study to avoid overestimated growth predictions. The effects of intensification methods are already partly reflected in the applied growth models. Slightly higher fertilization area by Hynynen et al. (2015) compared to our scenarios with similar harvesting volumes, could be explained by the fact that only upland forests were fertilized in our study. Hynynen et al. (2015) applied fertilization also on drained peatlands, using the models of Moilanen et al. (2005). The fertilization gain in upland forest sites was calculated with the same models (Kukkola and Saramäki 1983) in both studies.

The effect of DNM on the growth of drained peatland stands was predicted in both studies as suggested by Hökkä et al. (2000) and Hökkä and Kojola (2002). The clearly higher DNM areas by Hynynen et al. (2015) compared to this study could be explained by the fact that we simulated DNM only in 40% of stands meeting the DNM criteria. We wanted to avoid simulation of larger DNM areas than the present, because ditches of poorly growing drained peatlands are not anymore recommended to be maintained in the future due to low economic profitability, which will decrease the DNM area from the current (Äijälä et al. 2014). We also assumed decreasing marginal benefit in growth and economic profitability with increasing DNM area. The NFI plots did not either include information on whether the stand would benefit from DNM. The criticism against DNM is also increasing, and therefore large DNM areas in the coming decades may not represent a likely future. In our study, the lower growth gain of DNM, compared to fertilization and use of improved regeneration material, may be partly explained by the smaller potential area of DNM.

Although the area of DNM, as well as that of forest fertilization, could be higher than simulated in this study, the growth increments and economic profitability produced by these treatments would become smaller when the treated area increases and the treatments are used in a less optimal way. In addition, increasing the area of these treatments would increase their harmful environmental impacts. For example, the increase of N fertilization and DNM areas may increase nutrient leaching, runoff of water, sedimentation and erosion of solid particles and carbon emissions from the soil (Saura et al. 1995; Saarsalmi and Mälkönen 2001; Finér et al. 2010; Hedwall et al. 2014; Saarsalmi et al. 2014; Ojanen 2015). Fertilization may also decrease berry crops (Issakainen and Moilanen 1998) and mushroom yields (Ohenoja 1994). Repeated fertilization may also decrease the timber quality, and increase browsing (Saarsalmi and Mälkönen 2001; Hedwall et al. 2014).

Our study ignored the expected growth increase of boreal forests under the climate change (Kellomäki et al. 2008). It also ignored the expected increases in various potential abiotic and biotic risks to forests, which could at least partly cancel the expected increase in forest productivity under climate change (Valinger and Lundqvist 1992; Peltola et al. 2010; Pukkala et al. 2014b; Subramanian et al. 2016; Thom and Seidl 2016; Möykkynen et al. 2017; Reyer et al. 2017). For example, the higher share of Norway spruce might lead to a larger risk of biotic and abiotic damages (Kellomäki et al. 2008; Peltola et al. 2010; Subramanian et al. 2016; Thom and Seidl 2016). Therefore, future studies should analyze in more detail the combined effects of intensified silvicultural practices and climate change on timber production and other ecosystem services such as biodiversity and carbon sequestration, taking into account the vulnerability of forest to abiotic and biotic risks.

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Table 1.

Variables describing study area, sample plots, and stand volumes by three regions in Finland. The area includes only forest land assigned to timber production and the volumes represent the year 2016.

	Southern Finland	Central Finland	Northern Finland	Whole Finland
Area, million ha	5.62	5.39	8.38	19.39
Area one sample plot represents, ha	2974	3869	5977	4139
Number of sample plots	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 and other broadleaves volume, million m^3	167	126	99	392

Table 2.

Saw log and pulpwood harvesting targets for each 10-year period in the *Basic*, *Breeding*, *Fertilization*, *Ditching* and *All* scenarios (million m^3 yr^{-1})

		Scenario			
		60[a]	70	80	90
Southern Finland	Saw log	11.96[b]	13.95	15.95	17.94
	Pulpwood	13.16	15.35	17.55	19.74
	Sum	25.12	29.30	33.49	37.68
Central Finland	Saw log	7.86	9.66	10.48	11.78
	Pulpwood	11.47	13.38	15.29	17.20
	Sum	19.32	23.04	25.76	28.98
Northern Finland	Saw log	3.59	4.19	4.79	5.39
	Pulpwood	9.24	10.78	12.32	13.86
	Sum	12.83	14.97	17.11	19.25
Whole Finland	Saw log	23.41	27.80	31.21	35.11
	Pulpwood	33.87	39.51	45.16	50.80
	Sum	57.28	67.31	76.37	85.91

[a] = average annual harvesting target, million m^3 yr^{-1}

[b] = average annual harvesting volume target in 10-year period, million m^3 yr^{-1}

Table 3.

Specifications of timber assortments for the main tree species used in scenario analysis. Same dimensions (top diameters, cm, and lengths, m) were used in all regions, whereas road side timber prices (€ m^{-3}) were considered by regions. SF = southern Finland, CF = central Finland, NF = northern Finland.

	SF	CF	NF	Whole Finland	
	€/m^{-3}	€/m^{-3}	€/m^{-3}	Top diam., cm	Piece length, m
Pine saw log	58	55	54	16	4.3
Pine pulpwood	29	28	25	6	2.7
Spruce saw log	56	54	53	17	4.3
Spruce pulpwood	30	29	26	6	2.7
Birch saw log	49	45	42	18	3.7
Birch pulpwood	29	29	28	6	2.7
Energy wood	20	20	20	3	2.0

Table 4.
Prices (€/ha) of silvicultural actions used in scenario analysis in different parts of Finland.

	Southern Finland	Central Finland	Northern Finland
Clearing of regeneration areas	204	190	142
Patch scarification	310	314	277
Disc trenching	235	227	174
Mounding	380	374	309
Seeding	245	260	203
Planting	698	703	631
Early cleaning of seedling stands	347	312	300
Tending of seedling stands	447	442	408
Improvement of young stands	450	394	343
Initial clearings of intermediate felling areas	265	260	186
Forest fertilization	403	384	377
Ditch network maintenance	245	245	245

Figure captions:

Fig. 1(a) Example of the growth response of pine stand to the nitrogen fertilization based on the model of Kukkola and Saramäki (1983). The nitrogen dose is 150 kg ha^{-1}, mean tree heights 10, 15, 20 and 25 m at the time of fertilization, site index (dominant height at the stand age of 100 years) 24 m. H = height at the time of fertilization; and **(b)** effect of ditch network maintenance on growth on drained peatlands according to the equation model used in this study (continuous lines) and the tabular model of Hökkä (dots). G = stand basal area, m^2 ha^{-1}, TS = Temperature sum, d.d.

Fig. 2 Average annual area of planting and sowing of forest sites (use of improved regeneration material) in scenarios having the annual harvesting target of 60, 70, 80 or 90 million m^3. Ref = realized average annual planting and sowing area during 2009-2013.

Fig. 3 Average annual area of fertilization and ditch network maintenance in scenarios having the annual harvesting target of 60, 70, 80 or 90 million m^3. Ref = realized average annual fertilization and ditch network maintenance area during 2009-2013.

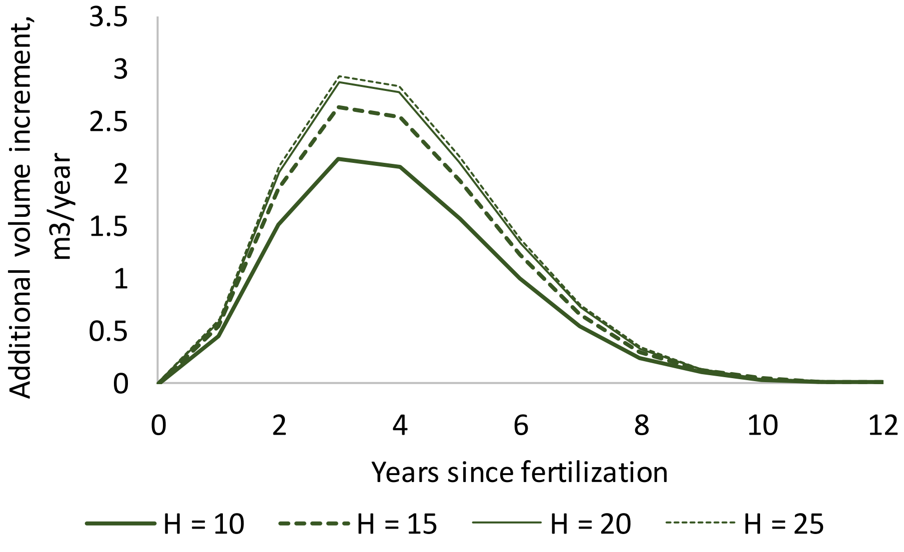
Fig. 4 Annual harvesting volume of saw log and pulpwood during different 10-year periods for *Basic* and *All* scenarios with 80 and 90 million m^3 annual harvesting targets. Ref = realized harvesting volume during 2004–2013.

Fig. 5 Growing stock in regions and in whole Finland for the scenario having 70 million annual harvesting target.

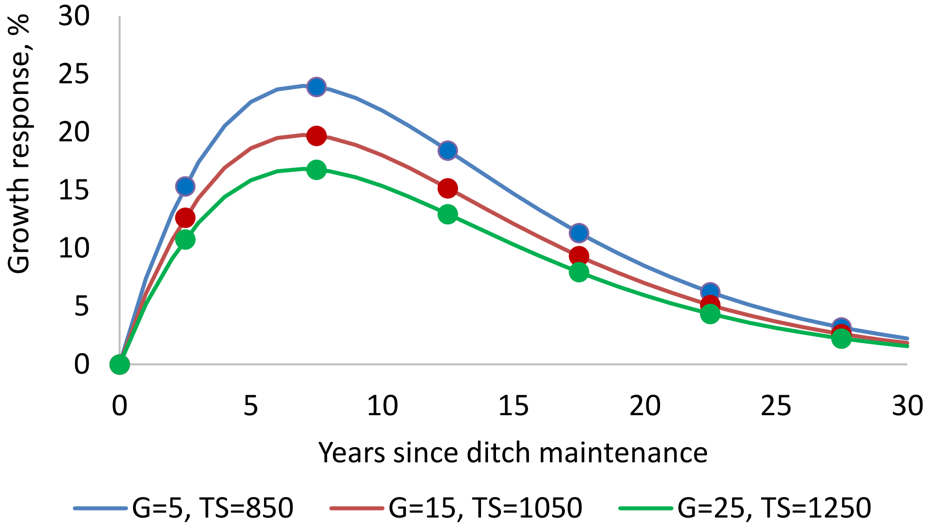
Fig. 6 Average annual timber production (harvested volume plus change in growing stock volume) during the 90-year simulation period in different scenarios.

Fig. 7 Periodical additional timber volume increment (million m^3 yr^{-1}) compared to the *Basic* scenario during different 10-year periods when the annual harvesting target is 70 million m^3 where (a) is the additional volume production during a certain 10-year period and (b) is the mean annual additional volume production by the end of certain 10-year period.

Fig. 8 Average annual addition in volume increment during a 90-year simulation period for different management intensification scenarios, as compared to *Basic70* scenario, when the annual harvesting volume is 70 million m^3.


Additional volume increment, m3/year
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
Years since fertilization
H = 10
H = 15
H = 20
H = 25

(a)


Growth response, %
30
25
20
15
10
5
0
0
5
10
15
20
25
30
Years since ditch maintenance
G=5, TS=850
G=15, TS=1050
G=25, TS=1250

(b)

Fig. 1

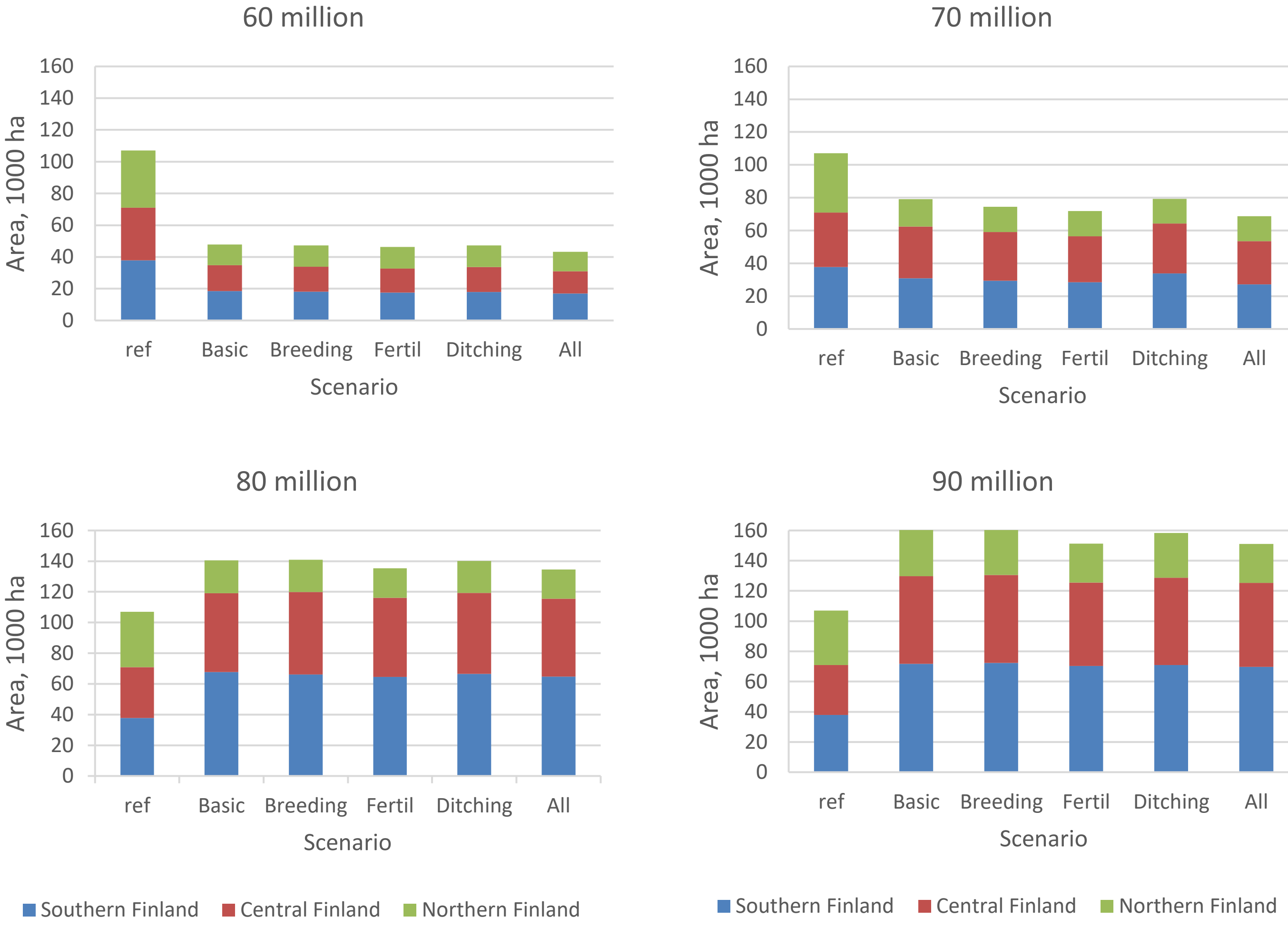
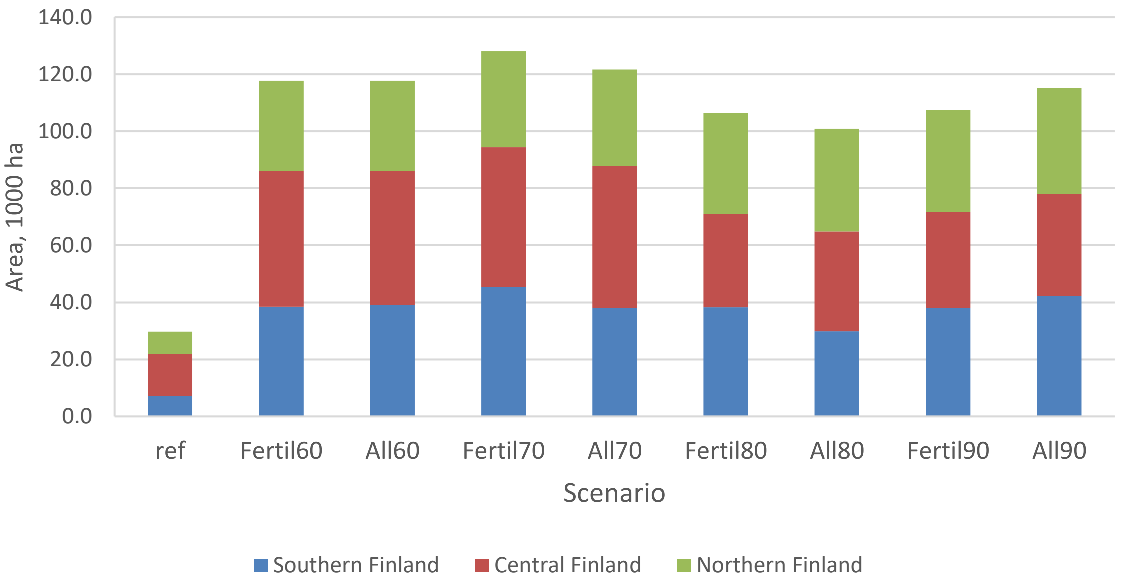

60 million
Area, 1000 ha
160
140
120
100
80
60
40
20
0
ref
Basic
Breeding
Fertil
Ditching
All
Scenario
70 million
Area, 1000 ha
160
140
120
100
80
60
40
20
0
ref
Basic
Breeding
Fertil
Ditching
All
Scenario
80 million
Area, 1000 ha
160
140
120
100
80
60
40
20
0
ref
Basic
Breeding
Fertil
Ditching
All
Scenario
90 million
Area, 1000 ha
160
140
120
100
80
60
40
20
0
ref
Basic
Breeding
Fertil
Ditching
All
Scenario
Southern Finland
Central Finland
Northern Finland
Southern Finland
Central Finland
Northern Finland

Fig. 2

Fertilization



Ditch network maintenance

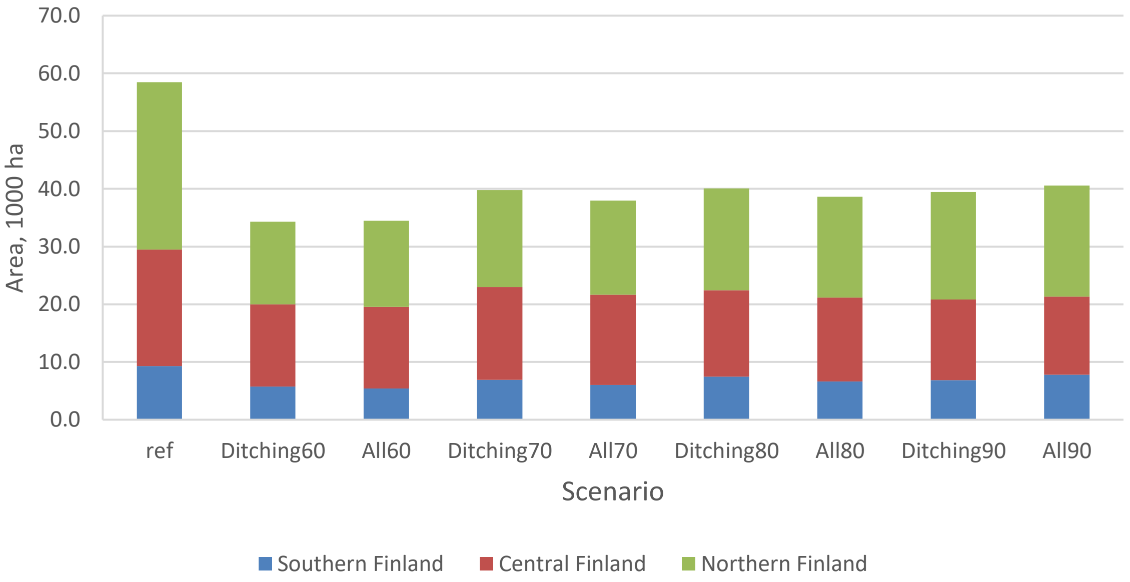


Fig. 3

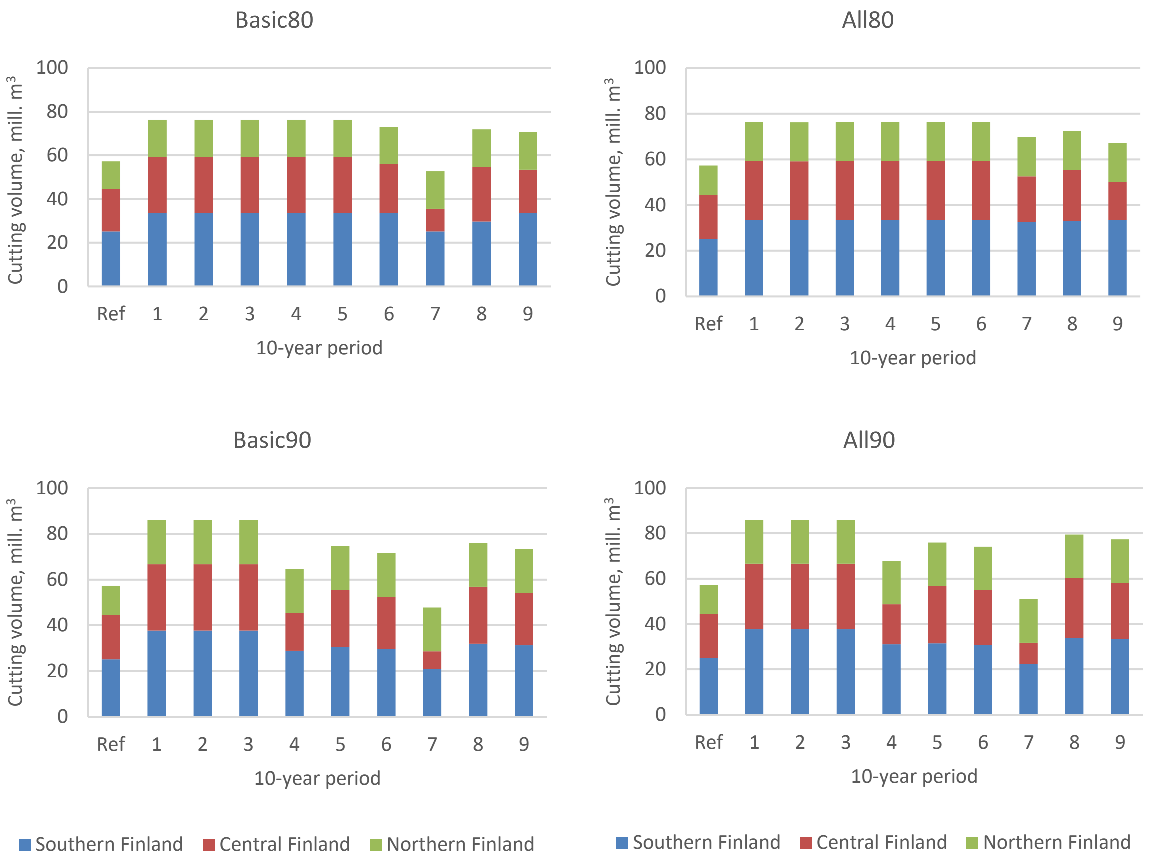

Basic80
All80
Basic90
All90
Cutting volume, mill. m3
100
80
60
40
20
0
Ref
1
2
3
4
5
6
7
8
9
10-year period
Southern Finland
Central Finland
Northern Finland

Fig. 4

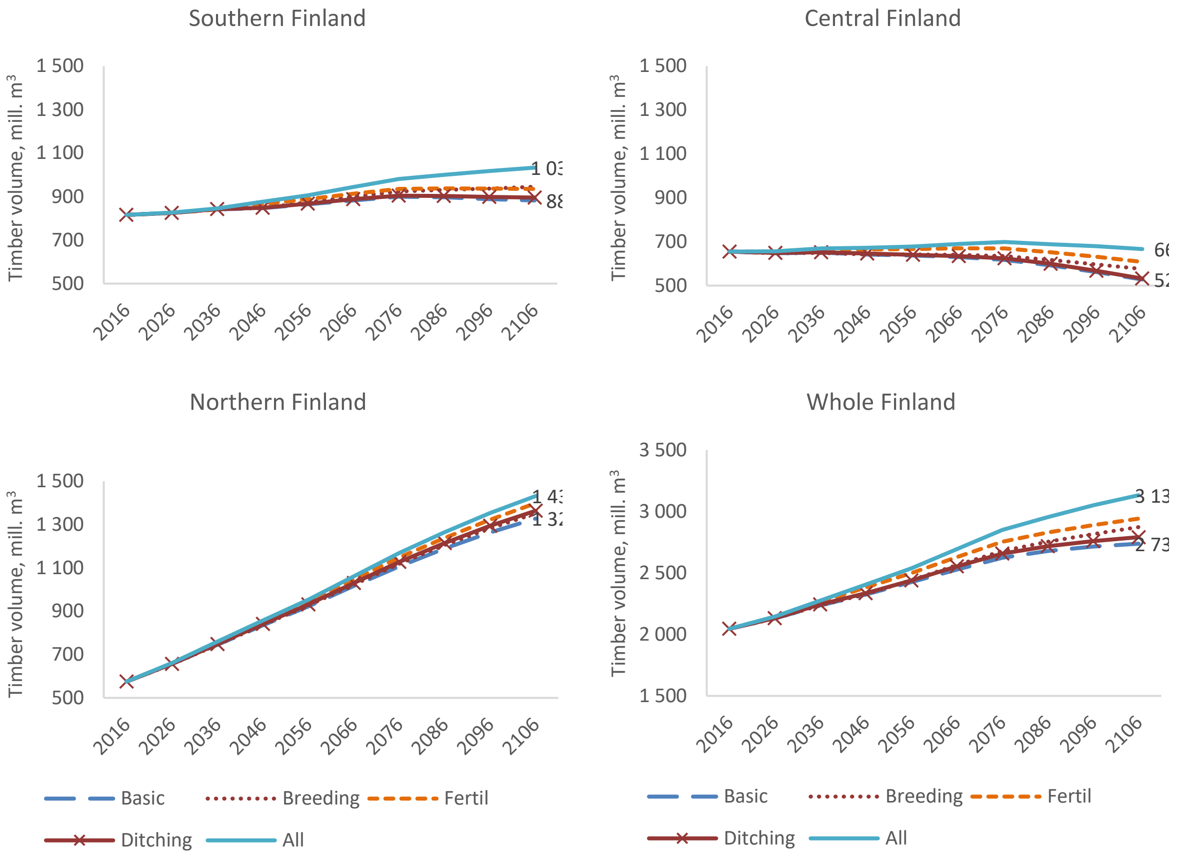

Southern Finland
Central Finland
Northern Finland
Whole Finland
Timber volume, mill. m³
1 500
1 300
1 100
900
700
500
3 500
3 000
2 500
2 000
1 500
2016
2026
2036
2046
2056
2066
2076
2086
2096
2106
1 03
88
66
52
1 43
1 32
3 13
2 73
Basic
Breeding
Fertil
Ditching
All

Fig. 5

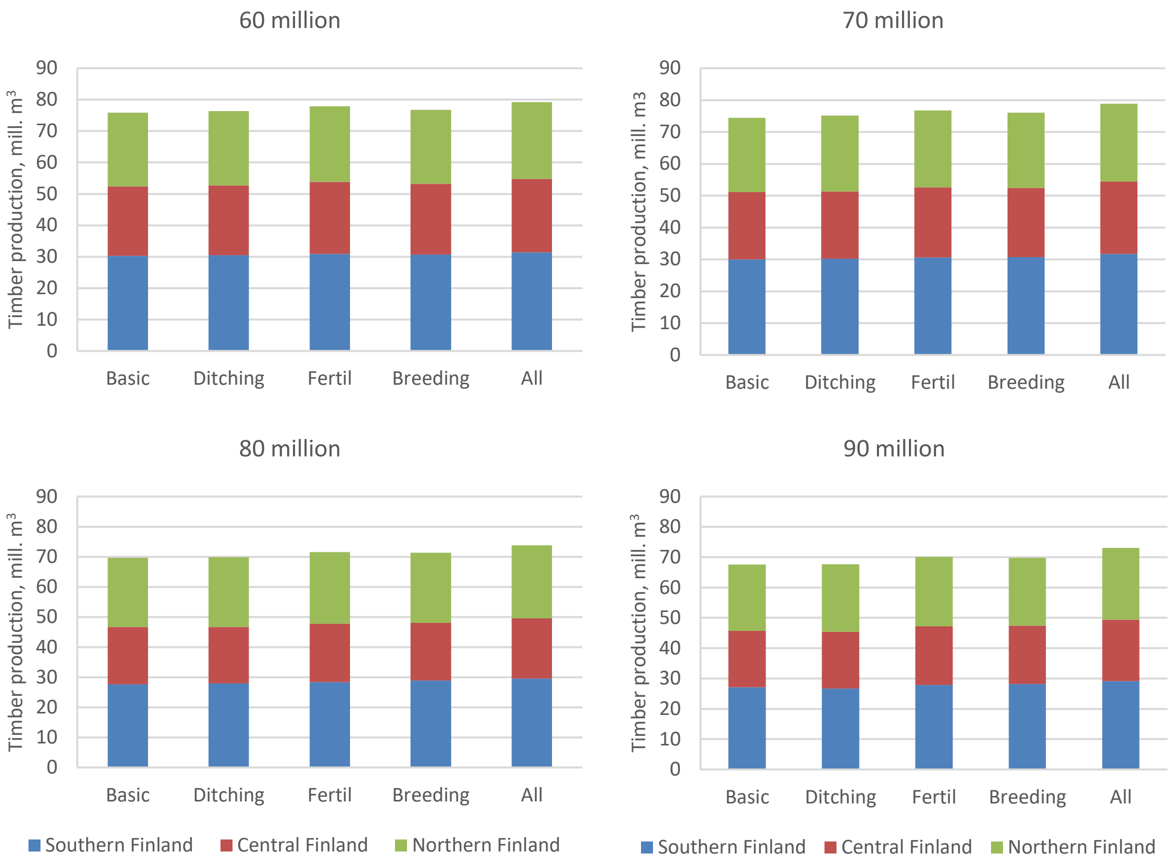
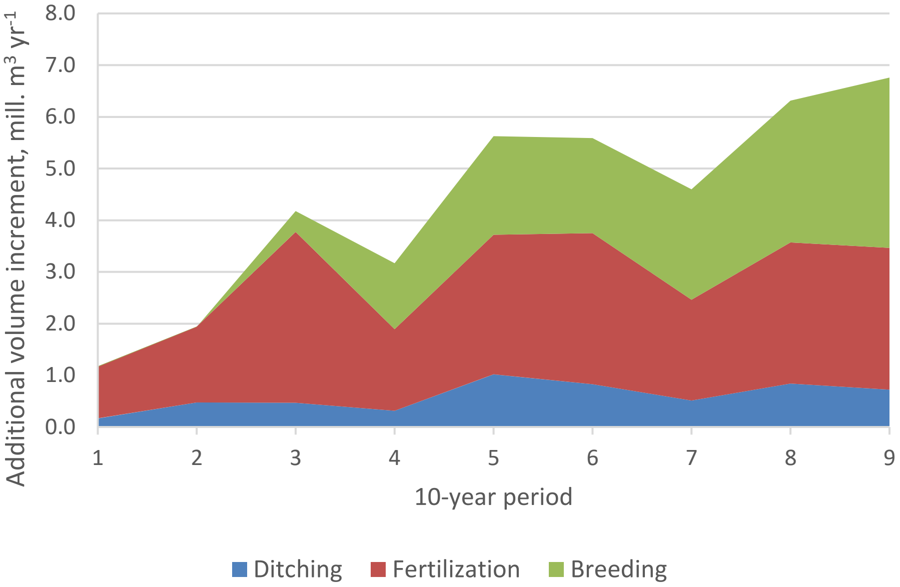
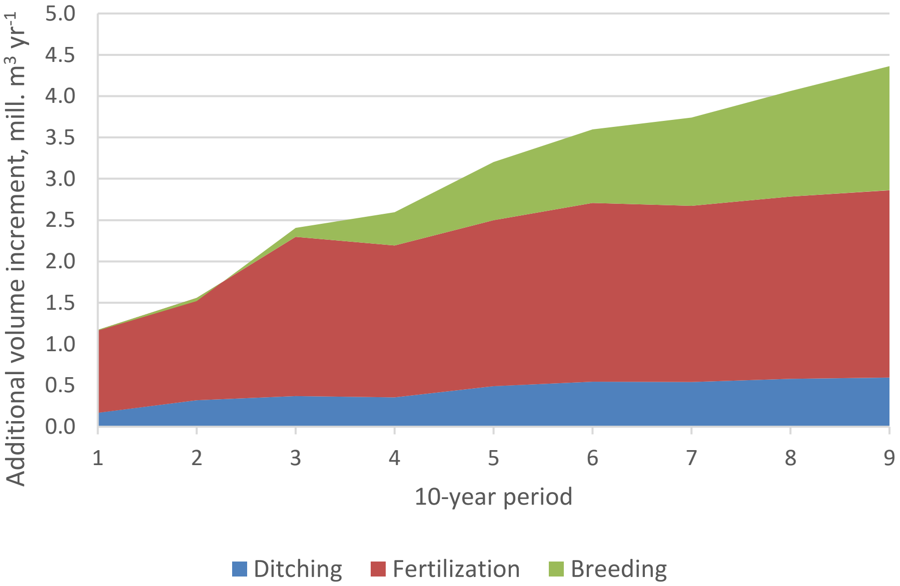

60 million
70 million
80 million
90 million
Timber production, mill. m³
Timber production, mill. m3
0
10
20
30
40
50
60
70
80
90
Basic
Ditching
Fertil
Breeding
All
Southern Finland
Central Finland
Northern Finland

Fig. 6

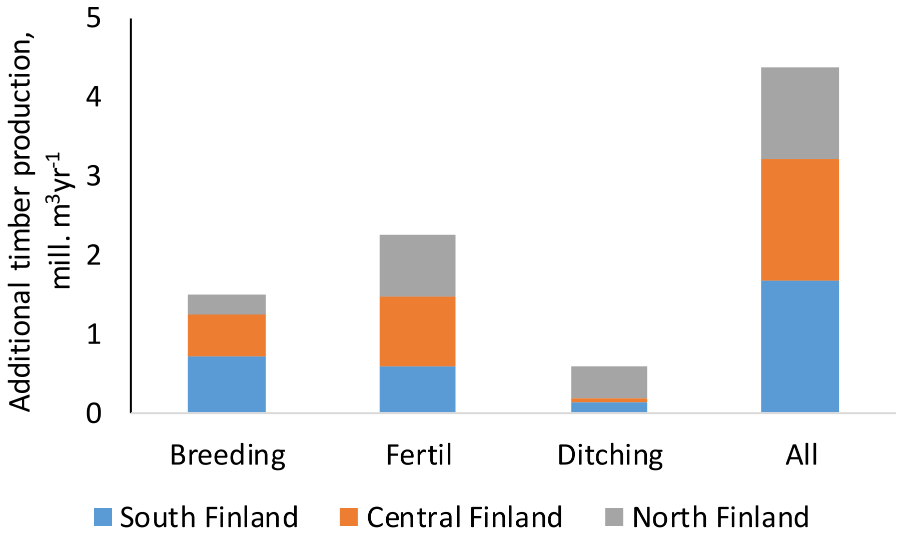

Additional volume increment, mill. m^3 yr^{-1}
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1
2
3
4
5
6
7
8
9
10-year period
🟦 Ditching
🟥 Fertilization
🟩 Breeding

(a)


Additional volume increment, mill. m^3 yr^{-1}
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
6
7
8
9
10-year period
🟦 Ditching
🟥 Fertilization
🟩 Breeding

(b)

Fig. 7



Additional timber production, mill. m3yr-1
0
1
2
3
4
5
Breeding
Fertil
Ditching
All
South Finland
Central Finland
North Finland

Fig. 8