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Effects of intensified silviculture on timber production and its economic profitability in boreal Norway spruce and Scots pine stands under changing climatic conditions

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The aim of this study was to examine how intensified silviculture affects timber production (sawlogs and pulpwood) and its economic profitability (net present value [NPV], with 2 per cent interest rate) based on forest ecosystem model simulations. The study was conducted on Norway spruce and Scots pine stands located on medium-fertile upland forest sites under middle boreal conditions in Finland, under current climate and minor climate change (the RCP2.6 forcing scenario). In intensified silviculture, improved regeneration materials were used, with 10–20 per cent higher growth than the unimproved materials, and/or nitrogen (N) fertilization of 150 kg ha^{-1}, once or twice during a rotation of 50–70 years. Compared to the baseline management regime, the use of improved seedlings, alone or together with N fertilization, increased timber production by up to 26–28 per cent and the NPV by up to 32–60 per cent over rotation lengths of 60–70 years, regardless of tree species (although more in spruce) or climate applied. The use of improved seedlings affected timber yield and NPV more than N fertilization. Minor climate change also increased these outcomes in Scots pine, but not in Norway spruce.

Introduction

In Finland, the current target is to increase the annual domestic wood harvest by up to 80 million m^3 yr^{-1} by 2030 in order to fulfil the increasing wood demand of the growing forest-based bioeconomy (The Finnish Bioeconomy Strategy, 2014). In 2017, the domestic wood harvest was already 72.4 million m^3 yr^{-1} (Official Statistics Finland (OSF), 2018) whereas it was about 60 million m^3 yr^{-1} in 2004–2013 (Peltola, 2014). The increasing demand for wood has raised concerns about the sustainability of increasing the domestic wood harvest. Although the annual wood harvest is still clearly lower than the total annual volume growth of Finnish forests (e.g. 107 million m^3 yr^{-1} in 2018; Statistics, 2019), forest biomass production per unit land area should be increased to better meet the diverse and increasing targets set for the future forest-based bioeconomy.

Many previous experimental and simulation-based studies have shown that, by increasing the intensity of silvicultural activities, timber production and its economic profitability can be increased per unit land area in Nordic forests (e.g. Nilsen, 2001; Saarsalmi and Mälkönen, 2001; Bergh *et al.*, 2014; Haapanen *et al.*, 2015). Timber production per hectare can be increased on upland forest sites by use of appropriate site-specific regeneration methods and materials, tending of seedling stands, commercial thinnings, and nitrogen (N) fertilization over a rotation (e.g. Hynynen *et al.*, 2015; Heinonen *et al.*, 2018a, b). In the long term, the use of improved regeneration materials could greatly increase timber production per unit land area in Nordic countries (e.g. Haapanen *et al.*, 2015). This is because the volume growth of seed orchard (half-sib and full-sib families) stock for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) is 10–25 per cent higher than that of unimproved stock, based on trials in Finland and Sweden (Rosvall *et al.*, 2002; Ruotsalainen, 2014; Haapanen *et al.*, 2016; Jansson *et al.*, 2017). The use of improved regeneration materials could gradually also provide significant economic benefits due to enhanced tree growth and earlier cuttings, despite the higher price of improved materials (Ahtikoski *et al.*, 2012, 2013). On the other hand, the lack of regeneration materials with high breeding gain still currently constrains its use in Finland, and especially in Norway spruce (Haapanen *et al.*, 2016). The use of clonal material with high breeding gain in conifers is also still limited in practical forestry due to the high cost and low availability of such seedlings (Högberg, 2003).

In the short term, forest biomass production can be increased the most in Norway spruce and Scots pine stands by using N fertilization on upland forest sites, where the limited availability of N currently clearly restricts growth more than the supply of water (e.g. Linder, 1987; Saarsalmi and Mälkönen, 2001; Hyvönen *et al*., 2008; Bergh *et al*., 2014). A single application of 150 kg N ha^{-1} can increase the volume growth by about 10–20 m^3 ha^{-1} (up to 22–36 per cent over a 10-year period) in middle-aged or older Norway spruce stands on mesic sites, and in Scots pine stands on subxeric sites, compared to non-fertilization (Kukkola and Saramäki, 1983; Mälkönen and Kukkola, 1991; Ingerslev *et al*., 2001; Nohrstedt, 2001; Bergh *et al*., 2014). However, the growth response may vary, largely depending on the N dose, site fertility, climatic conditions and stand structure (Ingerslev *et al*., 2001; Nilsen, 2001; Nilsson and Fahlvik, 2006; Bergh *et al*., 2014). Currently, about 150 kg N ha^{-1} is typically used in fertilization in Norway spruce and Scots pine on upland forest sites (Äijälä *et al*., 2014; Hedwall *et al*., 2014). For economic and operational reasons, it is recommended to use a relatively large N dose once, although the highest growth responses may be achieved by repeated N fertilization, using moderate amounts each time (Bergh *et al*., 2008; Hyvönen *et al*., 2008).

From the viewpoint of the forest owner, the economic profitability of forestry is determined by timber production (sawlogs and pulpwood), and especially by sawlog production. Fertilization can enhance the economic profitability of forest biomass production, by more rapid shifting stems from pulpwood size to sawlog size (Bergh *et al*., 2014). The combined use of N fertilization and improved regeneration materials on suitable upland forest sites may also enable earlier thinnings and the use of shorter rotation lengths (e.g. less than 80 years). This, together with an increased timber yield over a rotation, could compensate for the costs of more intensive silvicultural actions (Nilsson and Fahlvik, 2006).

Based on the most recent generation of global climate model projections (CMIP5), the mean annual temperature and precipitation are likely to increase in Finland by 2–6°C and 6–18 per cent, respectively, by 2100, based on the representative concentration pathways (RCPs) forcing scenarios, RCP2.6 and RCP8.5 (Ruosteenoja *et al*., 2016). At the same time, the atmospheric CO_2 concentration is expected to increase from the current value of 350 ppm (1981–2010) up to 430 and 940 ppm under RCP2.6 and RCP8.5, respectively. The projected climate change may increase forest growth and timber production on upland boreal forests in general, due to longer and warmer growing seasons, an increase in the supply of available N for growth, and higher atmospheric CO_2 concentrations (e.g. Poudel *et al*., 2012; Rytter *et al*., 2016; Kellomäki *et al*., 2008, 2018). On the other hand, the volume growth of Norway spruce could be reduced, especially under southern boreal conditions (partially also under middle boreal conditions), and on sites with reduced soil water availability (e.g. Mäkinen *et al*., 2001; Jyske *et al*., 2009) and under severe climate change (Kellomäki *et al*., 2008, 2018).

The effects of the intensity of individual silvicultural treatments (e.g. use/no use of improved regeneration material, thinning, fertilization) on forest biomass production can be studied in field experiments. However, the use of a process-based forest ecosystem model based analysis would make it possible to analyze the sensitivity of forest biomass (e.g. timber) production, and its economic profitability, simultaneously with the varying intensity of different silvicultural treatments and environmental conditions. In this sense, such modelling can provide valuable support for defining optimal forest management strategies for practical forestry under changing climatic conditions. So far, this has been done mainly with statistical growth and yield models which have been developed to support decision-making in practical forestry (e.g. Hynynen *et al*., 2005; Pretzch *et al*., 2008).

The aim of this study was to examine how intensified silviculture affects timber production (sawlogs and pulpwood) and its economic profitability (net present value [NPV], with a 2 per cent interest rate) based on process-based forest ecosystem model simulations. The study was conducted on Norway spruce and Scots pine stands on medium-fertile upland forest sites under middle boreal conditions in Finland, under current climate and minor climate change (the RCP2.6 forcing scenario). In intensified silviculture, improved regeneration materials were used, with 10–20 per cent higher growth compared to unimproved regeneration materials (seedlings), and/or N fertilization of 150 kg ha^{-1}, once or twice during a rotation of 50 to 70 years.

Methods

Outline of the ecosystem model used in the simulations

We used the process-based forest ecosystem model SIMA (Kellomäki *et al*., 2005, 2008) to simulate the growth and dynamics of forest stands over a rotation. The model has been parameterized for the main boreal tree species growing on upland forests throughout Finland (60°–70°N, 20°–32°E). In the model, the prevailing growing conditions and forest management practices affect the growth and mortality of trees in tree stands. The diameter growth of a tree is modelled as a function of the potential diameter growth, which is affected by the prevailing growing conditions: the temperature sum (Tsum, degree days [d.d.] > +5°C), light, soil moisture and nitrogen (N) availability (multiplier = 1 = no reduction, < 1 = reduction in diameter growth; see Figure 1). The potential diameter growth is also affected by the diameter of the tree, the atmospheric carbon dioxide (CO_2) concentration, and by the genotype (e.g. use of unimproved/improved regeneration materials with impacts on tree growth; see Routa *et al*., 2013 for more details; Figure 1). The tree diameter is also used to calculate the height of the tree, and in this sense, the genotype affects both diameter and height growth of a tree. The tree diameter is also used again to calculate the mass of different tree organs (foliage, branches, stem and roots), based on the allometric relationship between the diameter and mass of the tree components, respectively. The volume of the stem is calculated using the approach of Laasasenaho (1982).

The multiplier for the temperature sum is based on a downwards-opening parabola, with tree-species specific minimum, optimum and maximum values, which define the geographical distribution of tree species throughout the boreal zone. Furthermore, the effects of temperature increase on growth under climate change are calculated based on the monthly changes in the temperature sum during the potential growing season (April–September), compared with the current climate (see Kellomäki *et al*., 2018). The multiplier for light limits the growth of a tree, along with the vertical light availability (gradient) through the stand. The multiplier for soil moisture indicates the fraction of days with/without adequate soil moisture for growth at the site, in relation to the balance between precipitation and evaporation in the growing season. Furthermore, field capacity and wilting point define the maximal available soil water as a function of soil type. The multiplier for N indicates

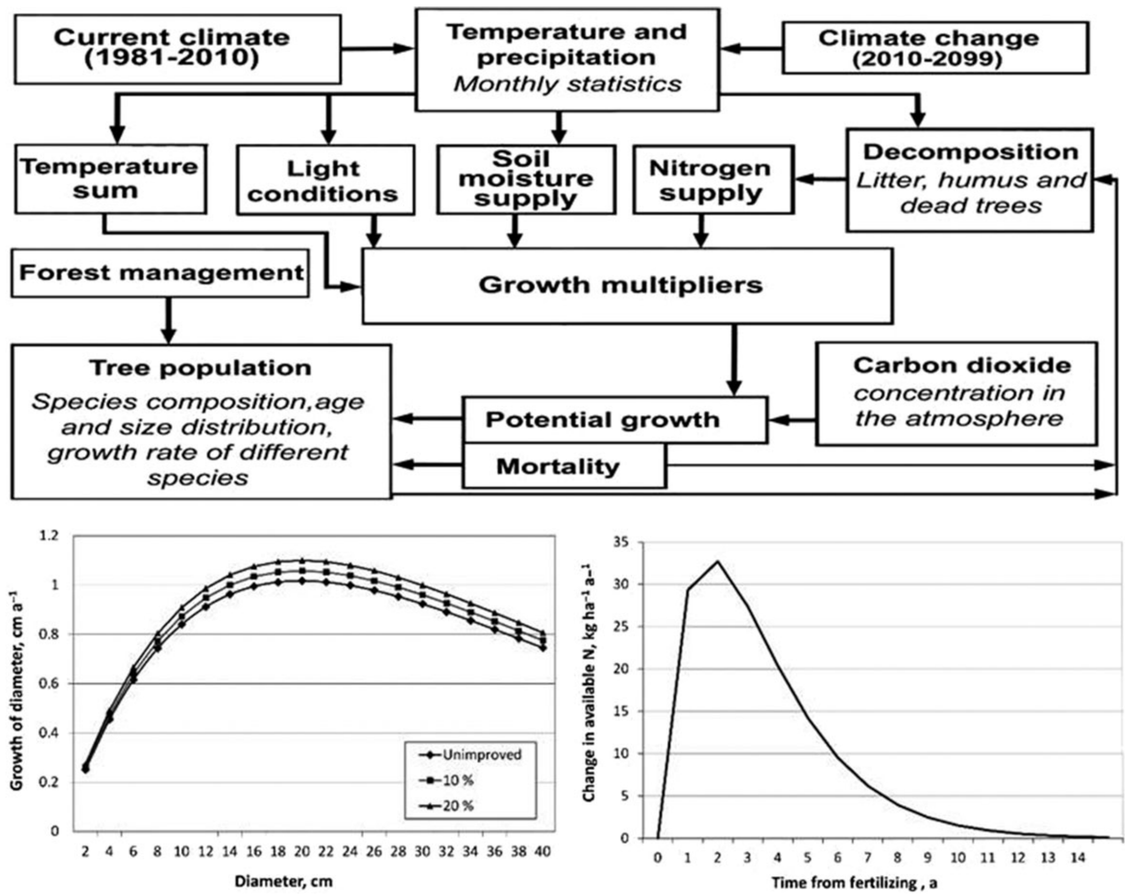

Figure 1 Outline of the forest ecosystem model SIMA used in the simulations (top), and conceptual illustration of the change in potential growth of diameter, as a function of tree diameter, when using 10 or 20 per cent improved regeneration materials (bottom left), and on the change in the available N over time, as a function of application of 150 kg N ha^{-1} (bottom right) in the SIMA model.

the N content in foliage in relation to the N available for growth in soil organic matter.

Litter from any living organ and the mortality of whole trees transfer carbon and N into the soil, where the litter and humus decay, releasing N for tree growth. Additionally, N fertilization increases N availability for growth (see Figure 1). The effect of N fertilization (i.e. the fraction of N fertilizer) on the annual growth of trees in a specific year is determined as a function of the time (years) since fertilization, and the total amount of fertilizer given, based on Kukkola and Saramäki (1983; and see Routa *et al*., 2011 for more details; Figure 1).

In the SIMA model, management options in even-aged forestry include the planting of seedlings (with either unimproved or improved growth) of different tree species, at the desired spacing, and the use of thinning, N fertilization and varying lengths of rotation. Natural regeneration is also possible but was not considered in this study. In the model, the timing and frequency of thinning (from below in this study) over the rotation are determined based on the predetermined thresholds for a basal area (cross sectional area of stems of all trees in a stand) and the dominant height of the trees in the stand, following the management recommendations given for practical forestry in Finland (see Äijälä *et al*., 2014). In the thinnings and final cut, only timber (pulpwood and sawlogs) was harvested in this study, and the yields of sawlogs and pulpwood were determined based on the given minimum top diameters for these (in this study 15 and 6 cm).

The model runs on an area of 100 m^2 and on an annual basis. The simulations are based on the Monte Carlo technique, due to the stochastic events involved, e.g. the regeneration and mortality of trees. The probability of a tree dying is affected also by the reduction in diameter growth. Each model run is one realization of all possible time courses of the forest ecosystem, and therefore the simulations are repeated many times (50 times in this study) to determine the mean tendency of the results over time.

Model performance versus other experimental and simulation-based studies

In this study, we compared the mean annual timber production (m^3 ha^{-1} a^{-1}) of the SIMA model and the empirical growth and yield model, Motti (Hynynen *et al*., 2002) under the current climate in thinned Scots pine and Norway spruce stands over 50-, 60- and 70-year rotation lengths on medium-fertile (Myrtillus type, MT) upland site types under middle boreal conditions (in Joensuu, eastern Finland, 62.39°N, 29.37°E). In the parallel simulations, we used the same initial site and stand characteristics (e.g. initial stand density, mean diameter and height and no breeding gain assumed), cutting rules for assorted timber (top diameter of pulpwood and sawlog assortment) and thinning rules (dominant height versus basal area thresholds for thinning from below). The comparison of the simulation results showed that Motti predicted up to 20 per cent and 9 per cent higher mean annual timber production (m^{3}ha^{-1}a^{-1}) for spruce and pine stands, respectively, than SIMA over one rotation, the difference between the models being the greatest with shorter rotations. These differences can be partially explained by Motti having been calibrated using National Forest Inventory (NFI11) data and the SIMA model using older NFI8 data. Previously, a reasonable agreement was found in the growth responses of Norway spruce and Scots pine stands to N fertilization between the SIMA model simulations (range of 39–63 per cent) and field measurements (range of 30–53 per cent), compared to the unfertilized cases (Mäkipää *et al.*, 1998). Previous simulations using the SIMA model (e.g. Kellomäki *et al.*, 2005, 2008) have also shown good agreement with the measured values of average volume growth on the permanent sample plots of the NFI throughout Finland.

Simulations, climate data and management regimes

The simulations were performed on Norway spruce and Scots pine stands, on medium-fertile sites in Joensuu, eastern Finland (62.39°N, 29.37°E). The simulations were run under current climate (1981–2010) and under minor gradual climate change, using in latter case multi-model mean (28 recent generation (CMIP5) global climate models) climate projection under the RCP2.6 forcing scenario for the period 2010–2099 (see Ruosteenoja *et al.*, 2016). The mean annual temperature sum was under the current climate (1981–2010) at about 1100 d.d. (+5°C), the average precipitation was about 532 mm and the average annual temperature was 2.4°C. Under climate change, the annual mean temperature and precipitation increased by 2°C and 6 per cent, respectively, by 2100 under the RCP2.6 forcing scenario (Ruosteenoja *et al.*, 2016). At the same time, the atmospheric CO_2 concentration increased from the current value of 350 ppm (1981–2010) up to 430 ppm by 2100 under the RCP2.6 forcing scenario.

At the beginning of the simulations, the average diameter of the seedlings was 3 cm, and the initial stand density was 2200 trees per hectare for both tree species. The thinning rules used in the simulations followed those recommended for these tree species in practical forestry in central Finland (Äijälä *et al.*, 2014). The simulations used an annual N deposition of 10.0 kg ha^{-1}, which was estimated based on the studies of Järvinen and Vänni (1994) and Kellomäki *et al.* (2005).

The alternative rotation lengths used in Norway spruce and Scots pine were 50, 60 and 70 years. One thinning (from below) was performed using a rotation length of 50 years, and one or two thinnings with rotation lengths of 60 and 70 years. N fertilization of 150 kg ha^{-1} was used only once during the rotation, at the time of the last thinning, or twice, at the time of thinnings. In addition to non-improved regeneration materials (basic seedlings), seedlings with 10 to 20 per cent better potential diameter growth (i.e. assumed breeding gain of +10 and +20 per cent, respectively) were used. Because the breeding gain affects potential diameter growth, the realized growth increases in diameter, height and volume are to some extent lower (e.g. in this study volume growth was on average 7–15 per cent higher for breeding gain of between 10 per cent and 20 per cent in thinned Scots pine and Norway spruce stands over 50–70 year rotation lengths). This is because growth is also affected by growth multipliers. The alternative management regimes used in the simulations are presented in Table 1.

Analysis of simulation outputs

In addition to the mean annual timber yield (pulpwood and sawlogs, m^3 ha^{-1} a^{-1}), the economic profitability of the management was calculated. For this purpose, the NPV (€ ha^{-1}) was calculated by discounting all harvesting and final felling incomes and management costs. The stumpage prices used in the study were based on the average prices between the years 2011 and 2016 (OSF, 2017), and all the calculated costs were based on the average values in 2010–2014 in Finland (OSF, 2015) (see Supplementary Data 1). The main aim of the analysis was to compare the effects of intensified management on simulation outputs in comparison to the baseline management. The timber yield and its economic profitability were analyzed using fixed rotation lengths as the criteria for final felling instead of basal area weighted diameter at breast height, which is the preferred criteria in practical forestry. This was done because it is not reasonable to compare the results between different time periods under gradually changing climate.

Results

Effects of intensive management on timber yield and net present value in Norway spruce stands

Timber yield. In the baseline management regime (no breeding gain(BG) and/or N fertilization), the annual mean timber yields were by 5.6, 5.7 and 6.3 m^3 ha^{-1} a^{-1} for rotation lengths of 50, 60 and 70 years, respectively, under the current climate (Figure 2). The use of improved regeneration materials alone, with 10 and 20 per cent higher growth rates (BG10 and BG20%), increased the timber yields by up to 12 per cent and 22 per cent during the rotation, compared to baseline management. The use of N fertilization alone, once or twice during the rotation, increased the timber yield by up to 7 per cent, compared to the baseline regime. The combined use of improved regeneration materials (BG20%), and N fertilization once (1 F) or twice (2 F) during the rotation, increased the timber yield the most, by up to 26–28 per cent (Figure 3).

Under the climate change, the relative differences between the baseline regime and other management regimes were similar to those under the current climate. The highest timber yields were obtained with 1F_BG20% for a 50-year rotation, both under the current climate and climate change (6.8 and 6.6 m^3 ha^{-1} a^{-1}). Over the 60- and 70-year rotations, the highest timber yields were obtained with 2F_BG20% both under the current climate (7.4 and 7.6 m^3 ha^{-1} a^{-1}) and under climate change (7.1 and 7.3 m^3 ha^{-1} a^{-1}). Furthermore, the mean annual timber yield was, on average, the highest for a rotation length of 70 years, regardless of climate applied (Figure 2). However, timber yields were, on average, 3–4 per cent lower under climate change. The intensified management increased the amount and proportion of sawlogs the most in a relative sense at shorter rotation lengths (Figure 2). Compared to the baseline management, 2F_BG20% increased the amount of sawlogs the most, regardless of rotation length, both under the current climate and under the climate change, i.e. by 71, 42 and 29 per cent and by 75, 31 and 32 per cent for rotation lengths of 50, 60 and 70 years, respectively.

Net present value. In the baseline management regime, the NPV2 per cent under the current climate was €2305, €3230 and €3899 ha^{-1} for rotation lengths of 50, 60 and 70 years, and under climate change it was €2065, €3299 and €3563 ha^{-1}, respectively. Under the current climate, the use of improved regeneration materials alone, with 10 and 20 per cent higher growth rates (BG+10% and BG+20%), increased the NPV by up to 19 per cent and 54 per cent, respectively, compared to baseline management (Figure 4). The use of N fertilization alone, once or twice during the rotation, increased the NPV by up to 7 per cent for rotation lengths of 50 and 60 years, compared to the baseline regime. The difference was marginal for a rotation length of 70 years (< 1 per cent).

Table 1 Alternative management regime descriptions with thinning years used in simulations for Norway spruce and Scots pine under the current and changing climate (RPC2.6). NS = Norway spruce, SP = Scots pine.

Climate	Rotation	1st thin, year		2nd thin, year		Description
CU		**NS**	**SP**	**NS**	**SP**	
0F_BG0%	50	36	29			No breeding gain, no fertilization
1F_BG0%		36	29			No breeding gain, 1x fertilization
0F_BG10%		34	27			Breeding gain 10%, no fertilization
1F_BG10%		34	27			Breeding gain 10%, 1x fertilization
0F_BG20%		32	26			Breeding gain 20%, no fertilization
1F_BG20%		32	26			Breeding gain 20%, 1x fertilization
0F_BG0%	60	36	29			No breeding gain, no fertilization
1F_BG0%		36	29			No breeding gain, 1x fertilization
2F_BG0%			29		49	No breeding gain, 2x fertilization
0F_BG10%		34	27		47	Breeding gain 10%, no fertilization
1F_BG10%		34	27		47	Breeding gain 10%, 1x fertilization
2F_BG10%			27		45	Breeding gain 10%, 2x fertilization
0F_BG20%		32	26	50	44	Breeding gain 20%, no fertilization
1F_BG20%		32	26	50	44	Breeding gain 20%, 1x fertilization
2F_BG20%		32	26	49	42	Breeding gain 20%, 2x fertilization
0F_BG0%	70	36	29	56	51	No breeding gain, no fertilization
1F_BG0%		36	29	56	51	No breeding gain, 1x fertilization
2F_BG0%		36	29	55	49	No breeding gain, 2x fertilization
0F_BG10%		34	27	54	47	Breeding gain 10%, no fertilization
1F_BG10%		34	27	54	47	Breeding gain 10%, 1x fertilization
2F_BG10%		34	27	52	45	Breeding gain 10%, 2x fertilization
0F_BG20%		32	26	50	44	Breeding gain 20%, no fertilization
1F_BG20%		32	26	50	44	Breeding gain 20%, 1x fertilization
2F_BG20%		32	26	49	42	Breeding gain 20%, 2x fertilization
RCP2.6		**NS**	**SP**	**NS**	**SP**	
0F_BG0%	50	36	27			No breeding gain, no fertilization
1F_BG0%		36	27			No breeding gain, 1x fertilization
0F_BG10%		34	25			Breeding gain 10%, no fertilization
1F_BG10%		34	25			Breeding gain 10%, 1x fertilization
0F_BG20%		32	24			Breeding gain 20%, no fertilization
1F_BG20%		32	24			Breeding gain 20%, 1x fertilization
2F_BG20%			24		38	Breeding gain 20%, 2x fertilization
0F_BG0%	60	36	27		47	No breeding gain, no fertilization
1F_BG0%		36	27		47	No breeding gain, 1x fertilization
2F_BG0%			27		44	No breeding gain, 2x fertilization
0F_BG10%		34	25		42	Breeding gain 10%, no fertilization
1F_BG10%		34	25		42	Breeding gain 10%, 1x fertilization
2F_BG10%			25		41	Breeding gain 10%, 2x fertilization
0F_BG20%		32	24		40	Breeding gain 20%, no fertilization
1F_BG20%		32	24		40	Breeding gain 20%, 1x fertilization
2F_BG20%		32	24	49	38	Breeding gain 20%, 2x fertilization
0F_BG0%	70	36	27	58	47	No breeding gain, no fertilization
1F_BG0%		36	27	58	47	No breeding gain, 1x fertilization
2F_BG0%		36	27	57	44	No breeding gain, 2x fertilization
0F_BG10%		34	25	55	42	Breeding gain 10%, no fertilization
1F_BG10%		34	25	55	42	Breeding gain 10%, 1x fertilization
2F_BG10%		34	25	54	41	Breeding gain 10%, 2x fertilization
0F_BG20%		32	24	51	40	Breeding gain 20%, no fertilization
1F_BG20%		32	24	51	40	Breeding gain 20%, 1x fertilization
2F_BG20%		32	24	49	38	Breeding gain 20%, 2x fertilization

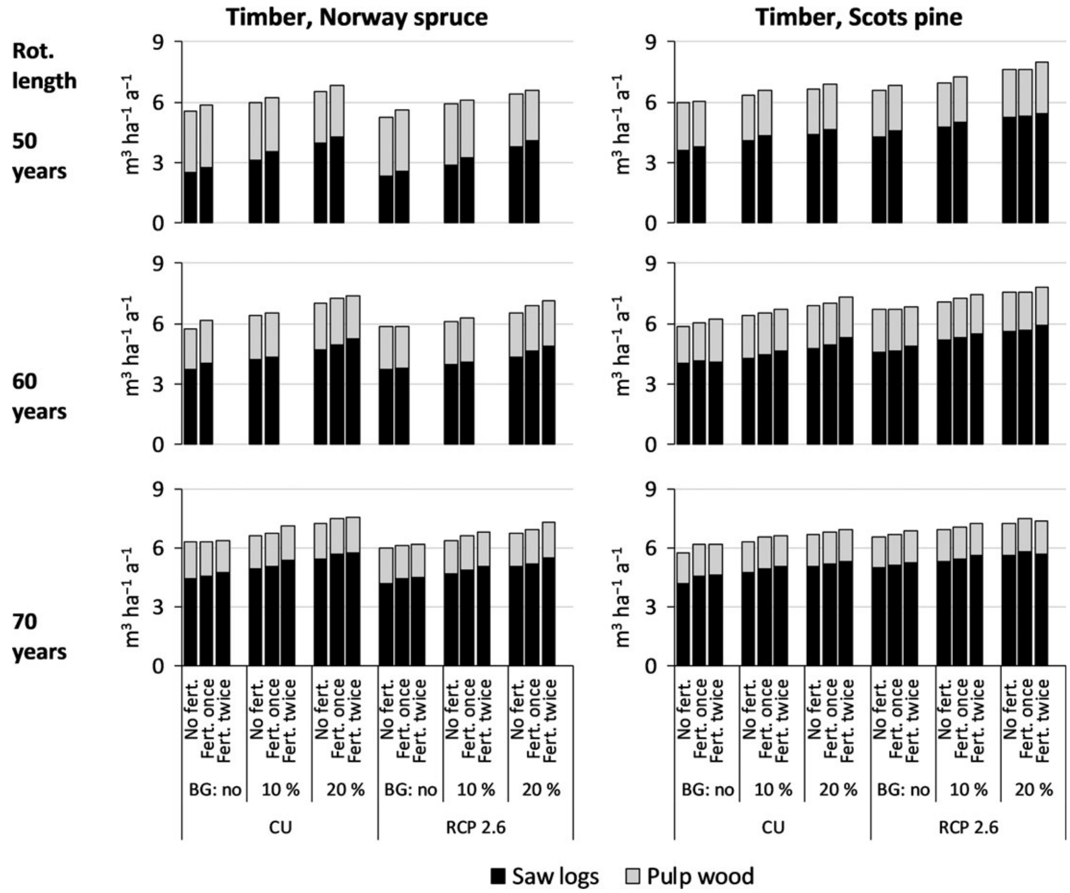

Figure 2 Effects of fertilization and improved regeneration materials on timber production (m^3 ha^{-1} a^{-1}) with rotation lengths of 50, 60 and 70 years under the current (CU) and changing (RPC2.6) climate in Norway spruce and Scots pine.

The combined use of improved regeneration materials (BG20%) and 1 F or 2 F N fertilization during the rotation increased the NPV by up to 60 per cent and 39 per cent, respectively, under the current climate, and relatively the most with shorter rotations. Under climate change, the corresponding increase was up to 27 per cent for a 60-year rotation, compared to baseline management (Figure 4). The relative differences between the baseline and intensified management regimes were similar for the 50- and 70-year rotations, regardless of climate scenario. The highest NPV was obtained with 1F_BG20% for a 50-year rotation both under the current climate and climate change (€3691 and €3458 ha^{-1}), and for a 70-year rotation under the current climate (€5025 ha^{-1}). The highest NPV was obtained with 2F_BG20% for a 60-year rotation both under the current climate and climate change (€4494 and €4175 ha^{-1}), and for a 70-year rotation under climate change (€4648 ha^{-1}).

Effects of intensive management on timber yield and net present value in Scots pine stands

Timber yield

In the baseline management regime, the annual mean timber yields were 6.0, 5.8 and 5.8 m^3 ha^{-1} a^{-1} for rotation lengths of 50, 60 and 70 years, respectively, under the current climate (Figure 2). The use of improved regeneration materials alone, with 10 and 20 per cent higher growth rates (BG10% and BG20%), increased the timber yield by up to 9 per cent and 18 per cent, during the rotation, compared to baseline management. The use of N fertilization alone, once or twice during the rotation, increased the timber yield by up to 7 per cent, compared to the baseline regime (Figure 3). The combined use of improved regeneration materials (BG20%) and 1 F or 2 F N fertilization during the rotation increased the timber yield the most, by up to 21 per cent and 26 per cent (Figure 3). The highest timber yield was obtained for a 50-year rotation under the current climate with 1F_BG20%, and under climate change with 2F_BG20% (6.9 and 8.0 m^3 ha^{-1} a^{-1}, respectively). For rotation lengths of 60 and 70 years, the highest yields were obtained under the current climate with 2F_BG20% (7.3 and 6.9 m^3 ha^{-1} a^{-1}). Under climate change, the highest yields were obtained with 2F_BG20% for a 60-year rotation and with 1F_BG20% for a 70-year rotation (7.8 and 7.5 m^3 ha^{-1} a^{-1}; Figure 2). The mean annual timber yield was, on average, the highest for a rotation of 60 years under the current climate, and for a rotation of 50 years under climate change.

Under climate change, the relative differences between the baseline and other management regimes were similar to those under the current climate. However, the timber yields were, on

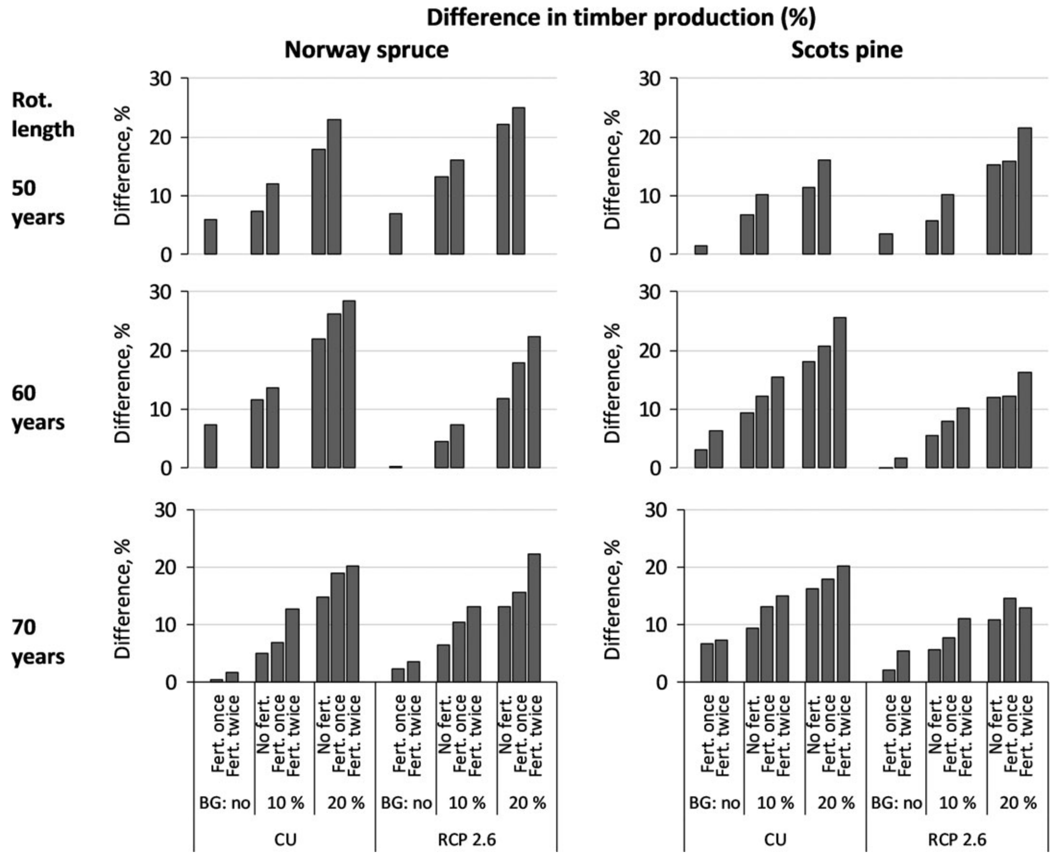

Figure 3 Effects of fertilization and improved regeneration materials on annual timber production ($m^3\ ha^{-1}\ a^{-1}$) as a difference (%) from baseline management, with rotation lengths of 50, 60 and 70 years under the current (CU) and changing (RPC2.6) climate in Norway spruce and Scots pine.

average, 9–13 per cent higher under climate change, regardless of rotation length (Figure 3). The intensified management clearly increased the amount and proportion of sawlogs, relatively mostly at shorter rotation lengths (Figure 2). Under the current climate, the use of 2F_BG20% increased the amount of sawlogs by up to 31 per cent, compared to the baseline management. Under climate change, the increase was by up to 28 per cent.

Net present value

In the baseline management regime, the NPV2 per cent was €3207, €3449 and €3627 ha^{-1} for rotation lengths of 50, 60 and 70 years, respectively, under the current climate. Corresponding values under climate change were €3920, €4288 and €4515 ha^{-1}, respectively. Under the current climate, the use of improved regeneration materials alone, with 10 and 20 per cent higher growth rates (BG+10% and BG+20%), increased the NPV2 per cent by up to 13 per cent and 27 per cent, compared to baseline management (Figure 4). The use of 1 F or 2 F N fertilization alone during the rotation increased under the current climate the NPV by up to 6 per cent for a rotation of 70 years, compared to baseline management. Under climate change, the difference was marginal, regardless of rotation length. The combined use of improved regeneration materials (BG+20%) and 1 F or 2 F N fertilization during the rotation increased the NPV under the current climate by up to 28 and 32 per cent, respectively, compared to baseline management, and by up to 23 per cent under climate change. Otherwise, under climate change, the relative differences between the baseline and other management regimes were quite similar, compared to those under the current climate.

The highest NPV was obtained with 1F_BG20% for a 50-year rotation under the current climate, and with 0F_BG20% under climate change (€3925 and €4797 ha^{-1}). The highest NPV was obtained with 2F_BG20% for a 60-year rotation under the current climate, and with 0F_BG20% under climate change (€4566 and €5277 ha^{-1}). The highest NPV was obtained with 0F_BG20% for a 70-year rotation under the current climate, and with 1F_BG20% under climate change (€4521 and €5210 ha^{-1}).

Discussion

Previous studies on the impacts of forest management and climate change on the timber yield and/or economic profitability of forestry in boreal Scots pine and Norway spruce stands (e.g. Garcia-Gonzalo *et al.*, 2007; ALRahahleh *et al.*, 2018), have not considered the impacts of using improved regeneration materials and/or N fertilization, alone or in interaction, with varying rotation lengths. In this work, we studied how much it was possible to increase the timber yield (sawlogs and pulpwood) and its economic profitability per unit land area in managed Norway

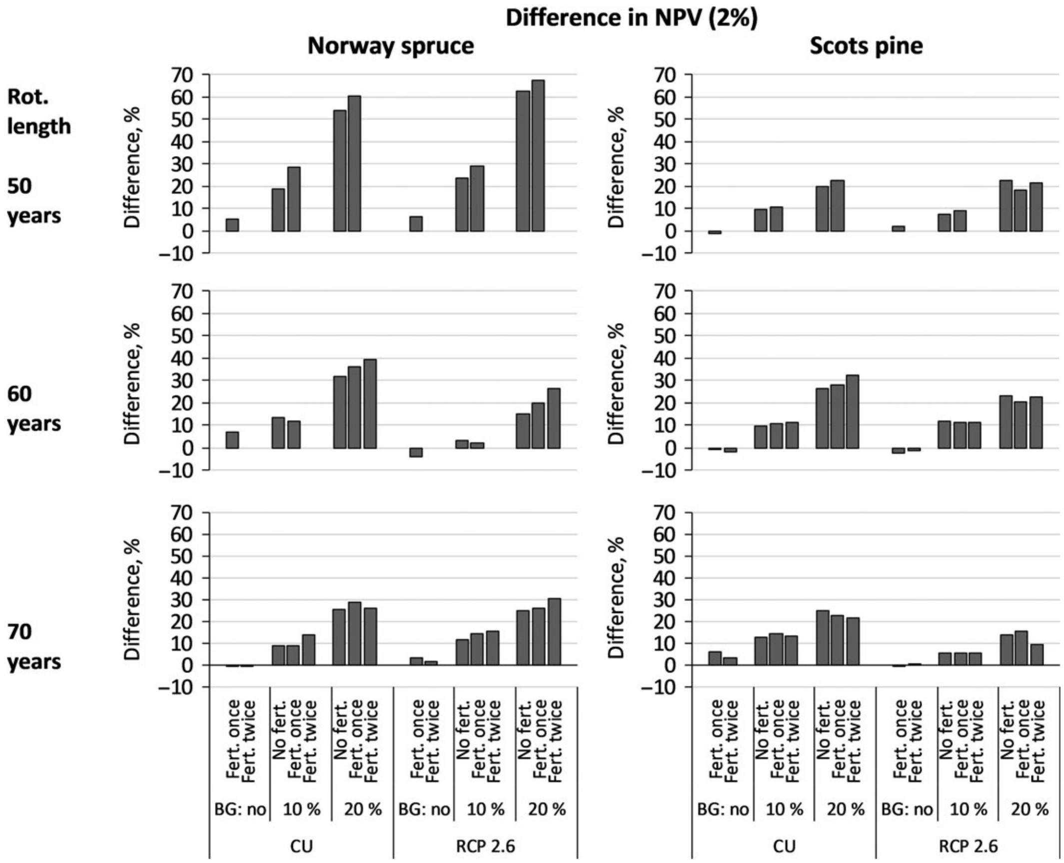

Figure 4 Effects of fertilization and improved regeneration materials on net present value (NPV2 per cent), as a difference (%) from baseline management, with rotation lengths of 50, 60 and 70 years under the current (CU) and changing (RPC2.6) climate in Norway spruce and Scots pine.

spruce and Scots pine stands on medium upland forest sites under middle boreal conditions by intensifying forest management by different methods. More specifically, based on forest ecosystem model simulations, we studied the effects of the use of improved regeneration materials (seedlings with 10 or 20 per cent higher growth rates compared to unimproved materials) and/or N fertilization of 150 kg ha^{-1}, once or twice, using different rotation lengths of 50, 60 and 70 years, under the current climate and minor climate change. These kind of analyses are needed because there is an urgent need to increase forest growth and timber supply per unit land area to meet the increasing and diversifying targets set for the forest-based bioeconomy, and the ambitious targets set for climate change mitigation as well through the sustainable and resource-efficient management and use of forests.

In this study, we assumed a breeding gain of 10–20 per cent, based on previous studies of growth responses of trees in relatively young seed orchard (half-sib and full-sib families) stock in Finland and Sweden (see, e.g. Rosvall *et al.*, 2002; Ruotsalainen, 2014; Haapanen *et al.*, 2016; Jansson *et al.*, 2017). This was because no long-term data were available in practical forestry for estimating the tree breeding gain. Based on our simulations, the timber yield (only pulpwood) increased in the first commercial thinning by up to 7–9 per cent in Norway spruce and Scots pine stands compared to baseline management, when improved regeneration materials with 10 or 20 per cent higher growth (without N fertilization) were used. Over the entire rotation, the corresponding increases were for a 50-, 60- and 70-year rotation lengths in Norway spruce stands 7–18, 12–22 and 5–15 per cent, and in Scots pine stands 7–11, 9–18 and 9–16 per cent, respectively. Because other implemented management measures, such as thinning and different rotation lengths, also affect forest growth and timber yield, a comparison of simulated breeding gain against measured breeding gain in young seed orchard stocks is not possible.

In the case of N fertilization, we used 150 kg ha^{-1} once or twice during the rotation at the time of the first thinning and/or last thinning before the final cut. This kind of N addition is currently practised in Norway spruce and Scots pine on upland boreal forest sites (see, e.g. Äijälä *et al.*, 2014; Hedwall *et al.*, 2014). In our study, compared to the baseline regime, the timber yield increased with fertilization of 150 kg N ha^{-1} once or twice during a rotation of 60 years (no breeding gain assumed) by up to 25 m^3 ha^{-1} in Norway spruce stands, and up to 11 m^3 ha^{-1} in Scots pine stands (see Appendices 2 and 3). This range is in agreement with previous experimental studies for these tree species in Nordic countries (see, e.g. Kukkola and Saramäki, 1983; Mälkönen and Kukkola, 1991; Ingerslev *et al.*, 2001; Nohrstedt, 2001; Bergh *et al.*, 2014). On the other hand, higher increases in timber yield can also be achieved by using a higher dose and/or repeated fertilization over short intervals as has been shown in some previous studies (see e.g. Nilsson and Fahlvik, 2006; Bergh *et al.*, 2008; Jacobson and Pettersson, 2010; Hedwall *et al.*, 2014).

Although fertilization can considerably increase the timber yield per unit land area, the various damage and environmental risks (e.g. leaching of nutrients) associated with intensive fertilization could be greater (Hedwall *et al.*, 2014). For example, the risks of wind and snow (or other) damage may be greatly increased by thinning and fertilization and especially if they are done at the same time (Valinger and Lundqvist, 1992). The risk of such damage is also highest during the first few years after these management interventions. Therefore, in practical forestry, fertilization is not recommended to be done at the same time with thinning in order to avoid increase in snow and wind damage risk (see Äijälä *et al.* 2014). In this study, we simulated fertilization at the same year than thinning for practical reasons. We did not consider in this study either the increasing abiotic and biotic damage risks to forests, which could at least partially cancel out any climate-change-induced productivity increases (Reyer *et al.*, 2017).

As a result of the use of improved regeneration materials and/or N fertilization, the forest growth increased and thinnings were performed in this study some years earlier, compared to the baseline management. The use of improved materials increased also the timber yield over a rotation in a relative sense more than did N fertilization alone, regardless of rotation length and tree species or climate applied (see Supplementary Data 2 and 3). The use of improved seedlings and N fertilization together increased the timber yield the most, by up to 28 per cent compared to the baseline management. Intensifying the management regime also clearly increased the amount and proportion of sawlogs (from total timber production), compared to the baseline management, and the most in a relative sense at shorter rotation lengths. The use of the most intensified management regime (2F_BG20%) increased the timber yield under the current climate by up to 90–98 m^3 ha^{-1} in Scots pine and Norway spruce stands, compared to the baseline regime. Correspondingly, under minor climate change, the increases were by up to 66 and 93 m^3 ha^{-1}, respectively.

In Norway spruce, the timber production was, on average, 3–4 per cent lower under a changing climate, whereas in Scots pine it was, on average, 9–13 per cent higher. Similarly, based on previous experimental studies, a warming climate favours the growth of Scots pine as opposed to Norway spruce, especially in southern boreal conditions on soils with low water-holding capacity (Mäkinen *et al.*, 2001; Jyske *et al.*, 2009). In the future, the expected higher summer temperatures and associated droughts (see Ruosteenoja *et al.*, 2018) will most probably decrease the growth of Norway spruce under boreal conditions (see, e.g. Kellomäki *et al.*, 2018). On the other hand, drought episodes and severe climate warming may also even decrease the growth of Scots pine (Henttonen *et al.*, 2015; Kellomäki *et al.*, 2018).

Increased sawlog yield affected positively the NPV, especially with the use of improved seedlings (BG20 per cent), but the corresponding effect of N fertilization varied. In Scots pine, the increase in timber yield did not compensate for the cost of fertilization in all cases (e.g. 1F_BG0% and 2F_BG20% regimes, with shorter rotations), regardless of the climate applied. The use of N fertilization together with improved seedlings was profitable (NPV2 per cent) in all simulation cases (both climates and tree species at all rotation lengths). Even with an interest rate of 3 per cent, N fertilization would have been profitable when improved seedlings were used in all simulation cases, as opposed to using unimproved seedlings (these results not shown in detail).

In general, intensive management (thinning, fertilization and breeding gain) resulted in increased growth rate and may thus decrease thinning interval and rotation length (in years). This would be the case if the timing and intensity of thinnings are driven by the development of dominant height and stand basal area, and if the timing of final felling is defined based on mean diameter of trees in a stand, which are the current forest management practices in Finland (see Äijälä *et al.* 2014). In our study, the timing and intensity of thinnings were driven by the development of dominant height and stand basal area. However, the timing of final felling was defined based on rotation length instead of mean diameter. On the other hand, the mean diameter of trees in a stand at the time of final felling was in different simulations in our study in the range of recommended mean diameter in practical forestry in Finland. The use of longer rotation length may decrease the NPV, and especially if the increase in saw log amount does not compensate the longer time needed for incomes and/or if higher interest rate is used in economic calculations. Based on this, the profitability of management regime including fertilization and the use of improved regeneration material may be greater than that reported in this study (see e.g. Ahtikoski *et al.*, 2012, 2013).

Our findings, that the use of better-growing seedlings and N fertilization were profitable investments for forest owners, with a 2 per cent interest rate, are in line with the findings of previous studies, which suggested that tree improvement (Ahtikoski *et al.*, 2012, 2013) and N fertilization (Jacobson and Pettersson, 2010; Simonsen *et al.*, 2010) are financially justifiable. Hynynen *et al.* (2015) and Heinonen *et al.* (2018a, b) also stated that, by intensifying forest management and using a combination of different methods (fertilization, improved regeneration materials, ditch network maintenance) at suitable sites, forest growth and timber supply could be increased in a resource-efficient way in different boreal regions, and without decreasing current forest resources at the national level. According to Hynynen *et al.* (2015), intensive management could be interpreted as a clear economic incentive to make long-term investments in forest management and forestry.

Conclusions

By intensifying forest management, we could increase forest growth and timber production per unit land area in a resource-efficient way. From the forest owner's perspective, the use of improved regeneration materials and N fertilization, both alone and especially together, in Norway spruce and Scots pine stands on medium-fertile upland forest sites, appear to be profitable investments under middle boreal conditions, both under the current and minor climate change. However, especially more severe climate change than assumed in this work could reduce largely the growth, timber yield and consequently also the economic profitability of forestry in Norway spruce, also under middle boreal conditions. On the other hand, more intensive management may at least partially compensate for the productivity losses expected otherwise for forest owners. In future studies, the increasing risks to forests from various abiotic and biotic forest damage should also be considered.

Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

None declared.

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References

Ahtikoski, A., Ojansuu, R., Haapanen, M., Hynynen, J. and Kärkkäinen, K. 2012 Financial performance of using genetically improved regeneration material of Scots pine (*Pinus sylvestris* L.) in Finland. *New For.* **43**, 335–348.

Ahtikoski, A., Salminen, H., Ojansuu, R., Hynynen, J., Kärkkäinen, K. and Haapanen, M. 2013 Optimizing stand management involving the effect of genetic gain: preliminary results for Scots pine in Finland. *Can. J. For. Res.* **43**, 299–305.

Äijälä, O., Koistinen, A., Sved, J., Vanhatalo, K. and Väisänen, P. (eds). 2014 *Hyvän metsänhoidon suositukset [Best practices for sustainable forest management]*. Metsätalouden kehittämiskeskus Tapion julkaisuja, 180. (In Finnish).

ALRahahleh, L., Kilpeläinen, A., Ikonen, V.-P., Strandman, H., Venäläinen, A. and Peltola, H. 2018 Effects of CMIP5 projections on volume growth, carbon stock and timber yield in managed Scots pine, Norway spruce and silver birch stands under southern and northern boreal conditions. *Forests* **9**, 208.

Bergh, J., Nilsson, U., Allen, H.L., Johansson, U. and Fahlvik, N. 2014 Long-term responses of Scots pine and Norway spruce stands in Sweden to repeated fertilization and thinning. *For. Ecol. Manag.* **320**, 118–158.

Bergh, J., Nilsson, U., Grip, H., Hedwall, P.-O. and Lundmark, T. 2008 Effects of frequency of fertilisation on production, foliar chemistry and nutrient leaching in young Norway spruce stands in Sweden. *Silva Fenn.* **42**, 721–733.

Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E. and Kellomäki, S. 2007 Effects of climate change and management on timber yield in boreal forests, with economic implications: a case study. *Ecol. Modell.* **209**, 220–234.

Haapanen, M., Hynynen, J., Ruotsalainen, S., Siipilehto, J. and Kilpeläinen, M.L. 2016 Realised and projected gains in growth, quality and simulated yield of genetically improved Scots pine in southern Finland. *Eur. J. For. Res.* **135**, 997–1009.

Haapanen, M., Janson, G., Nielsen, U.B., Steffenrem, A. and Stener, L.G. 2015 *The Status of Tree Breeding and Its Potential for Improving Biomass Production—A Review of Breeding Activities and Genetic Gains in Scandinavia and Finland*. Skogsforsk, p. 56.

Hedwall, P.-O., Gong, P., Ingerslev, M. and Bergh, J. 2014 Fertilization in northern forests—biological, economic and environmental constraints and possibilities. *Scand. J. Forest Res.* **29**, 301–311.

Heinonen, T., Pukkala, T., Asikainen, A. and Peltola, H. 2018a Scenario analyses on the effects of fertilization, improved regeneration material, and ditch network maintenance on timber production of Finnish forests. *Eur. J. For. Res.* **137**, 93–107.

Heinonen, T., Pukkala, T., Kellomäki, S., Strandman, H., Asikainen, A., Venäläinen, A., *et al* 2018b Effects of forest management and harvesting intensity on the timber supply from Finnish forests in a changing climate. *Can. J. For. Res.* **48**, 1124–1134.

Henttonen, H.M., Mäkinen, H., Heiskanen, J., Peltoniemi, M., Lauren, A. and Hordo, M. 2015 Response of radial increment variation of Scots pine to temperature, precipitation and soil water content along a latitudinal gradient across Finland and Estonia. *Agr. For. Meteorol* **198–199**, 294–308.

Hynynen, J., Ahtikoski, A., Siitonen, J., Sievänen, R. and Liski, J. 2005 Applying the MOTTI simulator to analyse the effects of alternative management schedules on timber and non-timber production. *For. Ecol. Manage.* **207**, 5–18.

Hynynen, J., Ojansuu, R., Hökkä, H., Siipilehto, J., Salminen, H. and Haapala, P. 2002. Models for predicting stand development in the MELA system. Finnish Forest Research Institute, Research Papers 835, 116 pp.

Hynynen, J., Salminen, H., Ahtikoski, A., Huuskonen, S., Ojansuu, R., Siipilehto, J., *et al* 2015 Long-term impacts of forest management on biomass supply and forest resource development: a scenario analysis for Finland. *Eur. J. For. Res.* **134**, 415–431.

Hyvönen, R., Persson, T., Andersson, S., Olsson, B., Ågren, G. and Linder, S. 2008 Impact of long-term nitrogen addition on carbon stocks in trees and soils in northern Europe. *Biogeochemistry* **89**, 121–137.

Högberg, K.A. 2003. Possibilities and limitations of vegetative propagation in breeding and mass propagation of Norway spruce. Doctoral thesis. Acta Univ. Agric. Sueciae, 294. SLU, Uppsala. ISBN 91-576-6528-1.

Ingerslev, M., Mälkönen, E., Nilsen, P., Nohrstedt, H.-Ö., Óskarsson, H. and Raulund-Rasmussen, K. 2001 Main findings and future challenges in forest nutritional research and management in the Nordic countries. *Scand. J. Forest Res.* **16**, 488–501.

Jacobson, S. and Pettersson, F. 2010 An assessment of different fertilization regimes in three boreal coniferous stands. *Silva Fenn.* **44**, 815–827.

Jansson, G., Hansen, J.K., Haapanen, M., Kvaalen, H. and Steffenrem, A. 2017 The genetic and economic gains from forest tree breeding programmes in Scandinavia and Finland. *Scand. J. Forest Res.* **32**, 273–286.

Jyske, T., Hölttä, T., Mäkinen, H., Nöjd, P., Lumme, I. and Spiecker, H. 2009 The effect of artificially induced drought on radial increment and wood properties of Norway spruce. *Tree Physiol.* **30**, 103–115.

Järvinen, O. and Vänni, T. 1994. Ministry of Water and the Environment Mimeograph, Finland 579, 68 pp. (In Finnish).

Kellomäki, S., Peltola, H., Nuutinen, T., Korhonen, K.T. and Strandman, H. 2008 Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **363**, 2341–2351.

Kellomäki, S., Strandman, H., Heinonen, T., Asikainen, A., Venäläinen, A. and Peltola, H. 2018 Temporal and spatial change in diameter growth of boreal Scots pine, Norway spruce, and birch under recent-generation (CMIP5) global climate model projections for the 21st century. *Forests* **9**, 118.

Kellomäki, S., Strandman, H., Nuutinen, T., Peltola, H., Korhonen, K.T. and Väisänen, H. 2005. Adaptation of forest ecosystems, forests and forestry to climate change. FINADAPT Working Paper 4, Finnish Environment Institute Mimeographs 334, Helsinki.

Kukkola, M. and Saramäki, J. 1983 Growth response in repeatedly fertilized pine and spruce stands on mineral soils. *Commun. Inst. For. Fenn.* **114**, 55.

Laasasenaho, J. 1982 Taper curve and volume functions for pine, spruce and birch. *Commun. Inst. For. Fenn.* **108**, 1–74.

Linder, S. 1987 Responses to water and nutrients in coniferous ecosystems. In *Potential and Limitations of Ecosystem Analyses, Ecological Studies*, **61**. Schulze E.D. and Zwölfer H. (eds). Springer, pp. 180–202.

Mäkinen, H., Nöjd, P. and Mielikäinen, K. 2001 Climatic signal in annual growth variation in damaged and healthy stands of Norway spruce [*Picea abies* (L.) Karst.] in southern Finland. *Trees* **15**, 177–185.

Mäkipää, R., Karjalainen, T., Pussinen, A., Kukkola, M., Kellomäki, S. and Mälkönen, E. 1998 Applicability of a forest simulation model for estimating effects of nitrogen deposition on a forest ecosystem: test of the validity of a gap-type model. *For. Ecol. Manage.* **108**, 239–250.

Mälkönen, E. and Kukkola, M. 1991 Effect of long-term fertilization on the biomass production and nutrient status of Scots pine stands. *Fertil. Res.* **27**, 113–127.

Nilsen, P. 2001 Fertilization experiments on forest mineral soils: a review of the Norwegian results. *Scand. J. Forest Res.* **16**, 541–554.

Nilsson, U. and Fahlvik, N. 2006 Ekonomisk analys av praktisk produktionsoptimering i granplanteringar (Economical analysis of operational use of nutrient optimisation in young stands of Norway spruce). In *Slutrapport för fiberskogsprogrammet*. Bergh J. and Oleskog G. (eds). SLU, Southern Swedish Forest Research Centre, pp. 1–17.

Nohrstedt, H.-Ö. 2001 Response of coniferous forest ecosystems on mineral soils to nutrient additions; a review of Swedish experiences. *Scand. J. Forest Res.* **16**, 555–573.

Official Statistics of Finland (OSF) 2015. Silvicultural and forest improvement work: Costs 2014 [online]. Helsinki: Natural Resources Institute Finland. Available at: http://stat.luke.fi/en/silvicultural-and-forest-improvement-work-costs-2014_en (Accessed 10 March 2018)

Official Statistics of Finland (OSF) 2017. Volumes and prices in roundwood trade 2016 [online]. Helsinki: Natural Resources Institute Finland. Available at: http://stat.luke.fi/teollisuuspuun-kauppa-2016_fi (Accessed 15 February 2018)

Official Statistics of Finland (OSF) 2018. Total roundwood removals and drain [online]. Helsinki: Natural Resources Institute Finland. Available at: https://stat.luke.fi/en/roundwood-removals-and-drain (Accessed 12 November 2018)

Peltola, A. (ed). 2014 *Finnish Statistical Yearbook of Forestry*. Finnish Forest Research Institute, p. 428.

Poudel, B.C., Sathre, R., Bergh, J., Gustavsson, L., Lundström, A. and Hyvönen, R. 2012 Potential effects of intensive forestry on biomass production and total carbon balance in north-central Sweden. *Environ. Sci. Policy* **15**, 106–124.

Pretzch, H., Grote, R., Reineking, B., Rötzer, T.H. and Seifert, S.T. 2008 Models for forest ecosystem management: a European perspective. *Ann. Bot.* **101**, 1065–1087.

Reyer, C., Bathgate, S., Blennow, K., Borges, J.G., Bugmann, H., Delzon, S., *et al* 2017 Are forest disturbances amplifying or cancelling out climate change-induced productivity changes in European forests? *Environ. Res. Lett.* **12** (3), 034027.

Rosvall, O., Jansson, G., Andersson, B., Ericsson, T., Karlsson, B., Sonesson, J., *et al* 2002. Predicted genetic gain from existing and future seed orchards and clone mixes in Sweden. Helsinki: Metsäntutkimuslaitoksen tiedonantoja – The Finnish Forest Research Institute, Research Papers 842, 71–85.

Routa, J., Kellomäki, S., Kilpeläinen, A., Peltola, H. and Strandman, H. 2011 Effects of forest management on the CO_2 emissions of wood energy in integrated production of timber and energy biomass. *GCB Bioenergy* **3**, 483–497.

Routa, J., Kellomäki, S., Strandman, H., Bergh, J., Pulkkinen, P. and Peltola, H. 2013 The timber and energy biomass potential of intensively managed cloned Norway spruce stands. *GCB Bioenergy* **5**, 43–52.

Ruosteenoja, K., Jylhä, K. and Kämäräinen, M. 2016 Climate projections for Finland under the RCP forcing scenarios. *Geophysica* **51**, 17–50.

Ruosteenoja, K., Markkanen, T., Venäläinen, A., Räisänen, P. and Peltola, H. 2018 Seasonal soil moisture and drought occurrence in Europe in CMIP5 projections for the 21st century. *Clim. Dynam.* **50** (3–4), 1177–1192.

Ruotsalainen, S. 2014 Increased forest production through forest tree breeding. *Scand. J. Forest Res.* **29**, 333–344.

Rytter, L., Ingerslev, M., Kilpeläinen, A., Torssonen, P., Lazdina, D., Löf, M., *et al* 2016 Increased forest biomass production in the Nordic and Baltic countries—a review of current and future opportunities. *Silva Fenn.* **50**, 1–33. article id 1660.

Saarsalmi, A. and Mälkönen, E. 2001 Forest fertilization research in Finland: a literature review. *Scand. J. Forest Res.* **16**, 514–535.

Simonsen, R., Rosvall, O., Gong, P. and Wibe, S. 2010 Profitability of measures to increase forest growth. *For. Policy Econ.* **12**, 473–482.

Statistics database 2019 [online]. Helsinki: Natural Resources Institute Finland. Available at: statdb.luke.fi (Accessed 6 February 2019)

The Finnish Bioeconomy Strategy – Sustainable growth from Bioeconomy 2014. Edita Prima Ltd, 17 pp.

Valinger, E. and Lundqvist, L. 1992 Influence of thinning and nitrogen fertilization on the frequency of snow and wind induced stand damage in forests. *Scott. For.* **46**, 311–332.