Effects of forest management intensity and climate change severity on volume growth, timber yield, carbon stocks, and the amount of deadwood in Scots pine, Norway spruce and silver birch stands in boreal conditions

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Abstract:

We studied how management intensity and climate severity affect volume growth, timber yield, carbon stocks, and the amount of deadwood in Scots pine (*Pinus sylvestris* (L.), Norway spruce (*Picea abies* (L.) Karst.) and silver birch (*Betula pendula* Roth.) dominated stands in the Republic of Karelia and Arkhangelsk region of northwest Russia. Using the forest ecosystem model (SIMA) under different climates (current and representative concentration pathway scenarios, RCP4.5 and RCP8.5), no-thinning, low, medium, and high intensity thinning rotational forestry regimes were simulated. Under RCPs, the volume growth and timber yield (5-53%), carbon stocks (1-22%), and deadwood amounts (11-75%) increased for all Scots pine and silver birch stands. The use of low intensity management increased volume growth and carbon stocks (3-16%) and deadwood amount (up to 60%) under RCPs, but not timber yield (±3%) in these stands. For Norway spruce stands, the volume growth (5-26%), timber yield (23-75%), and carbon stocks (5-15%) decreased under RCP8.5, but deadwood amount increased (up to 142%). Intensive management increased volume growth (4-19%), timber yield (4-63%), carbon stocks (up to 14%) and deadwood amounts (up to 49%). Our results highlight that effects of climate severity and management intensity are site and species-specific for Eurasian's boreal forests.

Keywords: Boreal tree species, ecosystem carbon stock, deadwood, timber yield, volume growth.

1. Introduction

With 30% of the world's forest area, boreal forests have a large potential in provisioning multiple ecosystem services (Gauthier et al. 2015), including biodiversity, timber, recreation, and climate change mitigation through sequestrating and storing carbon from the atmosphere. A variety of studies have assessed the effects of climate change on dynamics of boreal forests of northern Europe (e.g. in Finland) and the provisioning of ecosystem services under various environmental conditions and management regimes (Tikkanen et al. 2012; Mazziotta et al. 2014; Leppä et al. 2020; Shanin et al. 2021; Triviño et al. 2023). However, few studies have addressed such impacts in boreal forests of Russia, which account for 20% of global growing stock (FAO and UNEP 2020) and have a large timber production and carbon sink capacity (Leskinen et al. 2020; Schepaschenko et al. 2021).

Scots pine (*Pinus sylvestris* (L.)), Norway spruce (*Picea abies* (L.) H. Karst.), Silver birch (*Betula pendula* Roth.) and Downy birch (*Betula pubescens* Ehrh.) are economically the most important tree species in boreal forests of continental Europe. Currently, their growth is limited by a relatively short growing season (typically from May to August), low summer temperatures, and the supply of nutrients (Hyvönen et al. 2007). Under a changing climate, in addition to the warming and lengthening of the growing season, increasing atmospheric CO_2 concentration may also increase the growth of forests regardless of tree species (Ellsworth et al. 2012; Kellomäki et al. 2008, 2018). However, e.g. in southern Finland, the climatological growing environment has already been optimum for Norway spruce and near to optimum for Scots pine (Kellomäki et al. 2018). While deciduous tree species (e.g. birches) are expected to benefit the most from climate warming (Kellomäki et al. 2018).

Overall, the provisioning of ecosystem services is affected by different factors such as prevailing environmental conditions (climate, site), the magnitude of projected climate change, forest structure (age, tree species composition), and forest management intensity as well as natural disturbances (Briceño-Elizondo et al. 2006a, b; Alrahahleh et al. 2017, 2018; McDowell et al. 2020). Provisioning of a variety of ecosystem services in managed forests may also have both synergies and trade-offs (Díaz-Yáñez et al. 2021). For example, forest carbon stocks positively correlate with the amount of deadwood, which is an important biodiversity indicator as boreal forests accommodate numerous saproxylic (deadwood demanding) species (Tikkanen et al. 2007; Stokland 2012). In turn, carbon stocks and deadwood amounts are negatively affected by timber harvesting (Triviño et al. 2015; Pohjanmies et al. 2017; Díaz-Yáñez et al. 2021).

In boreal forests of continental Europe, northwest Russia is unique in that it retains large intact areas of primary forests (Yaroshenko et al. 2001). In such forests, timber harvesting has been noted to entail biodiversity loss (Naumov et al. 2018). It is assumed that increasing forest management intensity in other forests will reduce the need to harvest primary forests (Shorohova et al. 2019; Dobrynin et al. 2021). However, forest management practices in northwest Russia have typically relied on use of clear-cuts followed by natural regeneration without site preparation (Senko et al. 2018). Artificial forest regeneration with planting of seedlings and site preparation, and use of pre-commercial and commercial thinning, have been less common (Karjalainen et al. 2009; Nordberg et al. 2013). Interest in implementing higher intensity silvicultural practices, like those used in Finland and Sweden, has been increasing in northwest Russia, due to expected increases in merchantable timber yield and its economic profitability (Senko 2021). Yet, there are no systematic studies available on how use of higher intensity management together with the impacts of climate change may affect the volume growth, timber yield, ecosystem carbon stocks and the amount of deadwood in different boreal tree species stands in northwest Russia. This knowledge is important, as depending on the magnitude of climate change, prevailing environmental conditions, and forest structure (age, species), different and even opposing forest management measures may be needed.

This study assessed how forest management intensity, and climate change severity, affect volume growth, timber yield, ecosystem carbon stocks, and the amount of deadwood in boreal Scots pine, Norway spruce, and silver birch dominated stands grown on medium fertile site types in the Republic of Karelia and Arkhangelsk region of Russia. Forest ecosystem model (SIMA) simulations were performed at the stand level using i) no-thinning with final felling, ii) low or iii) medium intensity pre-commercial thinning together with commercial thinnings, and final felling (all cases), following regional forest management recommendations in Russia. Additionally, for comparison, iv) high intensity pre-commercial thinning together with commercial thinning and final felling, following forest management recommendations for Finnish forestry was used in simulations. A current climate (reference period of 1986-2005) and changing climates using representative concentration pathways, RCP4.5 and RCP8.5 scenarios by 2100 were utilized. We expected that there may exist large differences in tree species-specific responses to forest management intensity and climate change severity, affecting volume growth, timber yield, carbon stock and the amount of deadwood.

2. Materials and methods

2.1 Outline of the forest ecosystem model

A gap-type forest ecosystem model (SIMA, Kellomäki et al. 2008, 2018) was used to simulate the development of tree stands under different forest management intensities and climate projections. In the model, the annual diameter growth of trees is influenced by maximum (potential) diameter growth and environmental growth multipliers. Maximum diameter growth is calculated based on tree diameter and the atmospheric carbon dioxide (CO_2) concentration (for details, see Appendix A1), while environmental conditions determine if diameter growth is either restricted (multiplier <1) or allows for maximum diameter growth (multiplier = 1) based on species-specific responses to temperature sum (degree days > 5°C) of the growing season (April to September), light availability within a stand (along a vertical light gradient), soil moisture, and nitrogen availability within a stand (for details, see Appendix A1 and Fig. A1).

Tree height is calculated based on tree diameter and temperature sum of the growing season under the current climate to consider genotype differences in height to diameter ratios of trees at different latitudes (for details, see Appendix A1). Tree mass of foliage, branches, stem, and roots is calculated based on tree diameter. The probability of tree mortality is affected mainly by stand basal area and density in addition to the maximum age of trees. Independently, if no growth occurs for two consecutive years (induced by environmental growth multiplier responses), the probability of mortality increases (for details, see Appendix A1). Upon tree mortality, the mass of foliage and roots is accounted for as soil organic matter (litter), while depending on tree species, branch and stem mass remain as standing deadwood for a given number of years (dependent on probability, stem diameter, and environmental conditions contributing to stem mass decay), prior to being transferred to soil organic matter.

At the beginning of simulations, the properties of a tree stand are described in terms of tree species, with the number of trees per hectare in each diameter class of each tree species. The initial amount of soil organic matter (and carbon) and the nitrogen available for growth are given based on the site fertility type and regional temperature sum of the current climate. In the simulations, forest management may include control of stand density with pre-commercial and commercial thinning, final felling (clear-cut), and planting of seedlings with desired spacing and tree species. Timber is harvested, using minimum stem diameters of 16.5 and 6 cm for sawlog and pulpwood. The model simulations are carried out with a time step of one year on an area of 100 m^2, based on the Monte Carlo technique (i.e. certain events, such as the birth and death of trees, are stochastic events and only the mean tendency of many iterations is considered).

The model has been originally developed for Finnish conditions and validated against measured values of volume growth in National Forest Inventory plots of Finland and predicted values of volume growth with the empirical growth and yield model Motti (Hynynen et al. 2002) for the main boreal tree species of Finland (see Kellomäki et al. 2008, Routa et al. 2011a, b, 2012). The maximum diameter growth and height growth models of SIMA (see Appendix A1) have earlier been calibrated in the study of Ulianova (2018) for northwest Russia with growth and yield table data for unmanaged stands of Scots pine, Norway spruce, and silver birch (see Appendix A1). As a result of this calibration, simulated height and diameter of different tree species differed by less than 12% from corresponding values reported in growth and yield data (Ulianova 2018). Based on this, we assume that SIMA model can simulate reasonably well the development of boreal tree species stands in the Republic of Karelia and the Arkhangelsk region of northwest Russia.

2.2 Description of study locations, layout for model simulations, and data analyses

Stand level simulations were conducted for stands located at the Medvezhegorskoe forest district of the Republic of Karelia (northern site location) and the Cheremushkoe forest district of the Arkhangelsk region (southern site location) of Russia, belonging to the middle and southern boreal vegetation zones (Bonh et al. 2000; 2003). Three climate alternatives were used in the simulations to correspond to specific climatic conditions of the northern and southern site locations: A current climate (CU, reference period 1986-2005), and two climate change scenarios representing moderate (RCP4.5) and severe (RCP8.5) climate change. Climate change scenarios were represented by multi-model mean projections (% change in temperature, precipitation, and atmospheric CO_2 sums based on a standard spatial grid of 1°x 1°) extracted from 15 general circulation models (GCMs) under representative concentration pathway forcing scenarios of the Climate Model Intercomparison Project Phase 5 (CMIP5) for 2005-2100 (IPCC, 2013). Within each climate scenario, annual monthly data (temperature, precipitation, and atmospheric CO_2) was grouped within four distinct time periods: the reference period 1986-2005, an early 21st century (2005-2045), a mid-21st century (2046-2065), and an end 21st century period (2080-2100). CU data for mean monthly temperature, precipitation sums, and variation by month was derived from two meteorological stations representing the northern (63.27°N, 33.42°E) and southern (61.27°N, 46.72°E) locations. For RCP4.5 and RCP8.5, the annual monthly temperature and precipitation sums were created based on their percentage deviations from CU, using the same standard deviations established under CU to represent natural variation in climatic means. Transient annual climate projections were then created from linearly fitted mean temperature and precipitation values for the four time periods to form a continuous period for each climate projection (CU, RCP4.5, and RCP8.5). Based on RCP4.5 and RCP8.5 reference periods, the annual mean temperature may increase by 225-370% (4.5-7.4 °C), precipitation by 19-33% (114-191 mm), and atmospheric CO_2 concentration by 48-123% (172-442 ppm) by 2080-2100, compared to CU (Table 1).

(Table 1)

In this simulation study, forest site types corresponded to medium fertile mesic heath site types (Myrtillus, MT) with a field capacity of 25% and wilting point of 5% (e.g. Kellomäki et al. 2018) and sample plot data represented seedlings of 5 to 14 years in age (e.g. Gromtsev et al. 2003). Upland medium fertility forest site types were used in the simulations, as they were equally suitable environments for the studied tree species, allowing for comparison of tree species responses to different forest management alternatives and climates at northern and southern site locations. Initial composition of naturally regenerated stands consisted of a mixture of tree species and tree sizes that were managed to favor either Scots pine, Norway spruce, or silver birch in pre-commercial thinning (Table 2). The amount of deadwood (mortality induced standing and fallen trees) included only the deadwood formed during the simulation period, as information on initial deadwood amounts were not available for stands at the beginning of the simulations.

(Table 2)

The forest management alternatives used in the simulations employed site location- and tree species-specific treatments representing different management intensities, and rotation lengths present at the northern and southern site locations. Management alternatives included: i) no-thinning (NT) with final felling, ii) low (MK, MA1) or iii) medium (MA2) intensity pre-commercial thinning and commercial thinning with final felling, following regional forest management recommendations in Russia, and iv) high intensity (MF) pre-commercial thinning and commercial thinning with final felling, following forest management recommendations of Finland (e.g. Äijälä et al. 2019) (Table 3). The NT alternative represented a commonly used practice at both site locations. Management regimes with low intensity pre-commercial thinnings (MK, MA1) were also simulated for both areas, while management regimes with medium (MA2) intensity pre-commercial thinnings were available and simulated only at the southern site. Treatments were initiated according to the age of the stand and its basal area. In pre-commercial thinning, seedlings of non-target tree species were removed from overly dense seedling stands to achieve the desired stand density targets (stems ha^{-1}). Giving preference to either Scots pine, Norway spruce, or birch seedlings effectively removed multi-species components of managed stands during pre-commercial thinning. In commercial thinning, living trees with the lowest breast height diameter (cm) were removed until the desired basal area of the target species (predominantly Scots pine, Norway spruce, or silver birch) and management objectives were met (Table 3). In NT stands, high initial stocking of the target tree species (Table 2) combined with reduction of non-target tree species stocking density through high natural mortality (i.e. stem exclusion) decreased or removed entirely tree species mixtures by the end of the simulations.

Simulation results were analyzed for each study stand in terms of mean gross annual volume growth (m^3 ha^{-1} yr^{-1}), total harvested timber yield (m^3 ha^{-1}, pulpwood and sawlogs) from thinnings and final felling, mean forest ecosystem (tree and soil) carbon stock (Mg ha^{-1}), and the mean deadwood amount (fallen and standing volumes resulting from tree mortality, tons ha^{-1}) over the simulation period. Current climate (CU) was used as a reference for comparison of results for each tree species between climates for different forest management regimes used at the northern and southern site locations. MK and MA1 were used as a reference for comparison of results between management regimes under each climate at each site location.

(Table 3)

3. Results

3.1 Volume growth

Under the current climate, the mean annual volume growth of Scots pine, Norway spruce, and birch stands were at northern and southern site locations in the ranges of 4.9-7.1 m^3 ha^{-1} yr^{-1} and 7.7-10.8 m^3 ha^{-1} yr^{-1}, respectively, depending on management regime (Figs. 1 and 2). Volume growth of Scots pine (dominated) stands increased under the RCPs by 28-47% and 10-21% at the northern and southern site locations, compared to current climate, depending on management regime (Figs. 3 and 4). In Norway spruce (dominated) stands, volume growth increased by 10-14% under RCP4.5 and decreased by 5-13% under RCP8.5 at the northern site location (Fig. 3), while decreases of 4-26% were found at the southern site location under both RCPs (Fig. 4). In birch (dominated) stands, volume growth increased by 33-53% and by 32-41% at the northern and southern site locations under RCPs (Figs. 3 and 4).

Compared to MK at the northern and MA1 at the southern site location, volume growth of NT was 4-12% higher for Scots pine stands across all climates, being slightly higher at the northern site location (Figs. 3 and 4). Negligible differences in volume growth of Scots pine stands were found between MF and MK at the northern site location, while MF was 6-11% lower and MA2 displayed minor differences compared to MA1 at the southern site location, regardless of climate. For Norway spruce stands, volume growth of NT was 3-12% higher compared to MK at the northern site location across climates, while for the southern site location, MA1 remained at the same approximate level as MA1 under CU and RCP4.5 and decreased (4%) under RCP8.5. For MF and MA2, volume growth of Norway spruce was higher (up to 19%) compared to MK and MA1. In birch stands under NT, volume growth increased by 6-19% and 13-15% at the northern and southern site locations, compared to MK and MA1, regardless of climate. For MF, volume growth decreased by 8-10% and 13-14% at the northern and southern sites across climates, compared to MK and MA1.

3.2 Timber yield

Timber yields of Scots pine, Norway spruce, and silver birch stands were at northern and southern site locations in the ranges of 146-550 m^3 ha^{-1} and 266-601 m^3 ha^{-1}, respectively, under CU and depending on management regime (Figs. 1 and 2). Timber yields increased under the RCPs in Scots pine stands by 21-38% and 5-19% at the northern and southern site locations, compared to current climate, and to a lesser degree under RCP8.5 at both site locations (Figs. 3 and 4). In Norway spruce stands, timber yield increased under RCP4.5 at the northern site, but otherwise decreased across management regimes at northern and southern sites, with the largest decreases (23-75%) observed under RCP8.5 (Figs. 3 and 4). In birch stands, timber yield increased by 20-44% at northern and southern site locations along with the increasing severity of climate change.

When comparing timber yield of NT to MK and MA1, NT had 20-56% lower timber yields, regardless of climate and tree species with the largest decreases found in Norway spruces stands under RCP8.5 at northern and southern site locations (Figs. 3 and 4). Timber yield of MF and MA2 generally increased for Scots pine and Norway spruce across climates, compared to MK and MA1. This was particularly evident for Norway spruce at the northern site location under RCP8.5 (56%) and at the southern site location under both RCP4.5 and RCP8.5 (10-63%). In birch stands, use of MF and MA2 displayed minor timber yield differences compared to MK and MA1, regardless of climate and site location (Figs. 3 and 4).

3.3 Ecosystem carbon stocks

Under the current climate, ecosystem carbon stocks of Scots pine, Norway spruce, and birch stands were at the northern and southern site locations in the range of 58-97 tons ha^{-1} and 67-113 tons ha^{-1}, respectively, depending on management regime (Figs. 1 and 2). Carbon stocks were in Scots pine stands under RCPs 12-19% and 1-9% higher at the northern and southern site locations, compared to CU. In Norway spruce stands, carbon stocks increased only at the northern site location under RCP4.5. Under RCP8.5, decreases were observed at both site locations with the largest decreases found with low intensity management (NT), especially at the southern site location (Figs. 3 and 4). For birch stands, carbon stocks increased at both site locations under RCP4.5 and RCP8.5 with the largest increases found at the southern site location (20-44%). Carbon stocks were for Scots pine and birch stands higher among lower intensity management (NT and MF) compared to MK and MA1 at northern and southern site locations, regardless of climate (Figs. 3 and 4). However, this was not the case for Norway spruce stands at the southern site location under RCP8.5, where MF resulted in slightly higher carbon stocks than MA1 (Fig. 4).

3.4 Deadwood

The total amount of dead standing and dead fallen trees of Scots pine, Norway spruce, and birch stands was in the range of 4.5-24.7 tons ha^{-1} and 4.1-24 tons ha^{-1} at the northern and southern site locations under the current climate (Figs. 1 and 2). In Scots pine stands, deadwood amount increased by 11-46% under RCPs at both site locations, compared to the current climate. At the northern site location, the amount of deadwood for Norway spruce stands increased by 10-28% and 54-142% under RCP4.5 and RCP8.5, whereas it decreased at the southern site location under both RCPs. For birch stands, the amount of deadwood was 25-75% higher under RCPs at both site locations.

Management intensity affected the amount of deadwood to a large degree. Regardless of climate, for NT the amount of deadwood was for Scots pine stands 124-205% larger than for MK and MA1, at both site locations. For Norway spruce stands, NT displayed 45-191% larger amounts of dead wood at both site locations than MK and MA1. While for birch stands, the amount of deadwood under NT was 89-176% larger than for MK and MA1, depending on site location. With increasing management intensity for Scots pine and birch stands under MA2 and MF, deadwood amounts were typically lower (up to 60%) than for MK and MA1, at both site locations. At the southern site location, the amount of deadwood was for MA2 larger compared to MF for Scots pine and birch stands, regardless of climate. For Norway spruce stands at the northern site location, the amount of deadwood for MF was 12-59% larger than for MK across climates. The opposite was found to occur at the southern site location, where the amount of deadwood was for MF and MA2 lower than for MA1, regardless of climate (Figs. 3 and 4).

(Fig. 1)

(Fig. 2)

(Fig. 3)

(Fig. 4)

4. Discussion and Conclusions

High intensity rotational forestry, analogous to common management practices applied in Finland and Sweden, is often conveyed as the most prudent option for managed forest stands in boreal continental Europe, particularly from the timber production point of view. However, forest management intensity affects together with environmental (climate, site) conditions, the provisioning of different ecosystem services and their trade-offs (e.g. Briceño-Elizondo et al. 2006a; Felton et al. 2016; Alrahahleh et al. 2017, 2018; Pohjanmies et al. 2017; Diaz et al. 2021; Trivino et al. 2015, 2023), as was also found in this study. Management intensity also has a larger effect on development of forests and provisioning of ecosystem services (e.g. Alrahahleh et al. 2017; Heinonen et al. 2017; Diaz et al. 2021; Trivino et al. 2023) than the gradual climate change.

In this study, the mean annual gross volume growth (10-53%), timber yield (5-44%), ecosystem carbon stock (1-22%), and the amount of deadwood (11-75%) increased in Scots pine and birch dominated stands, regardless of management regime under climate change at both site locations. In the case of Norway spruce dominated stands, they increased (10-14%, 6-10%, 0-6%, and 10-28%) only at the northern site location and primarily under moderate climate change (RCP4.5). Under severe climate change (RCP8.5), decreases in volume growth (5-26%), timber yield (23-75%) and ecosystem carbon stocks (5-15%) were found for Norway spruce at both site locations, while increases in the amount of deadwood primarily occurred at the northern site location (54-142%).

Varied growth and mortality responses of tree species can be explained primarily by their differences in optimum growing conditions. In this study, early and severe mortality for Norway spruce and to a lesser degree for Scots pine decreased tree stocking under RCP8.5, particularly at the southern site location due to a combination of sustained reduction in growth from occurrence of high temperature sums (Fig. A1, Table A5) and higher likelihood of mortality from successive years below growth minimums, especially for Norway spruce (Appendix A1, Eq.2). Higher frequency in occurrence of high temperature sums, however, increased growth within the model for silver birch and Scots pine (RCP4.5) under climate warming (Table A5). Current temperature sum conditions were more optimal for forest growth at the southern site than at the northern site location, while mean monthly precipitation of the growing season remained similar (Table 1). For this reason, the differences in responses of tree species at the southern and northern site locations can also be partially explained by differences in prevailing environmental conditions (mainly temperature sum) of the two latitudes.

Although the volume growth of Norway spruce growth has been shown to be more sensitive to reduction of soil moisture than increase in temperature sum (Torssonen et al. 2015; Kellomäki et al. 2018), in this study reduction of growth due to soil moisture was found to be limited. The relatively high water holding capacity of the Myrtillus site type and low occurrence of dry days (days below the wilting point) led to a maximum of 2% of the growing season below the wilting point, far below species-specific maximum values that would severely limit growth through the multiplier effect (Fig. A1, Table A5).

The results of this study exhibit the same trend with findings of previous stand level simulation studies in Finland (e.g. Alrahahleh et al. 2018), where volume growth (39%) and timber yield (87%) decreased in Norway spruce stands, due to increased mortality (particularly at the southern site) under RCP8.5. The opposite development was observed for birch and Scots pine stands under moderate climate change (RCP4.5). In addition, results of this study aligned with forest simulation studies conducted in central Russia, where severe climate change (e.g. A1F1 emission scenario of HadCM3 model, IPCC, 2000) increased the net primary production by about 15% more in forests of northern than southern gradients (e.g. Shanin et al., 2011; Komarov and Shanin 2012), compared to the current climate. In this study, the mean annual gross volume growth of Scots pine and Norway spruce stands with NT were 20-26% higher under RCP8.5 at the northern site, compared to the southern site. However, the mean annual gross volume growth for birch remained relatively stable across both site locations.

In Finland and Sweden, pre-commercial and commercial thinnings are usually used in managed forests to decrease natural mortality, improve tree diameter growth and timber quality of trees, and to provide income for forest owners prior to final felling. In this simulation study, due to larger mortality, NT resulted in up to

21-40% lower timber yields for birch, Scots pine, and Norway spruce stands compared to other management regimes, regardless of climate and site location. However, NT resulted in the highest volume growth, ecosystem carbon stocks, and amount of deadwood in Scots pine and birch stands regardless of climate and site location. Observed decrease of annual volume growth at the stand level in relation to reduction of stand basal area (Mäkinen and Isomäki 2004) explains the higher mean annual volume growth of the NT treatments by comparison to more intensive treatments (including pre-commercial and commercial thinning), due to the relatively high density of remaining trees and their contribution to mean annual volume growth over the rotation. For NT, higher mean annual volume growth up to 3-31% for Scots pine and birch dominated stands as well as higher carbon stocks (8-41%) and amount of deadwood (88-467%) was present compared to other management regimes. For Norway spruce dominated stands, NT similarly displayed higher carbon stocks (7-31%) and amounts of deadwood (46-192%), but not consistently higher volume growth (up to 15% lower). This was due to high temperature sums increasing mortality under RCP4.5 (southern site location) and RCP8.5. NT also had a higher share of deciduous trees at the beginning of stand development compared to managed stands, which may have affected results.

Predicted increase in mortality under climate change, especially with NT but also with other management regimes, can be expected to provide suitable habitats for many saproxylic species (Hyvärinen et al. 2019), as they prefer sites with quantities of deadwood > 20 m^3 ha^{-1}. In Finland, the amount of deadwood in managed forests is approximately 6.4 m^3 ha^{-1} based on latest national forest inventory (NF13) (Kulju et al. 2023). Whereas, in natural forests the amount of deadwood may be up to 60-120 m^3 ha^{-1} (Peuhu and Siitonen 2011).

Low intensity management of Scots pine and birch stands under RCPs increased volume growth and carbon stocks (3-16%) and deadwood (up to 60%) with little difference between timber yields (±3%), compared to intensive management across site locations. For Norway spruce stands, the opposite occurred, as intensive management treatments displayed higher mean annual volume growth (4-19%) and timber yield (4-63%), while carbon stocks (up to 14%) and deadwood (up to 49%) with increased primarily at the northern site location, particularly under RCPs. The combination of higher temperature sums under RCPs influencing mortality and lower stand densities positively influencing individual tree growth generally benefited more intensive stand management for Norway spruce. In this study, initial stand characteristics and forest management regimes differed among and between tree species at the northern and southern site locations, which partially affected simulation outcomes and made generalization of findings difficult.

Depending on the severity of climate change, site- and region-specific management of different tree species will be crucial to sustain forest productivity and growth in the future. Use of low to medium intensity management regimes for birch and Scots pine may be suggested to balance provisioning of ecosystem services (i.e. ecosystem carbon stocks) and timber yield across site locations and climates. For Norway spruce higher intensity management with shorter rotations than used in our simulations are recommended, especially for southern site locations under climate change. Under severe climate change, to maintain forest growth, carbon stocks, timber yield, and to decrease mortality, increasingly growing Scots pine or birch stands and mixtures of deciduous and coniferous species may also be recommended as opposed to pure stands of Norway spruce, if forest site fertility is suitable (e.g. Felton et al. 2016; Pretzsch and Schütze, 2016; Huuskonen et al. 2021).

Climate change may also induce multiple damage risks to boreal forests (e.g. windthrow, heavy snow loads, drought, forest fires, and bark beetles), particularly at southern boreal latitudes and in unmanaged forests due to increased mortality of trees under severe climate change (e.g. Venäläinen et al. 2020). Such disturbances, may also, partially cancel out climate change induced productivity increases in managed boreal forests (Reyer et al. 2017). Considering the extent of existing boreal forests in Russia, silvicultural treatments, not limited to rotational forestry and their effect on not only stand, but landscape level ecosystem services should be further studied.

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Competing interests:

The authors declare there are no competing interests.

Data availability:

Data located and available upon request from the Faculty of Science, Forestry and Technology, University of Eastern Finland.

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Appendix A1. Outline of the forest ecosystem model and the calibrated model utilized for the Republic of Karelia and Arkhangelsk region of northwest Russia.

In the gap-type forest ecosystem model (SIMA, Kellomäki et al. 2008, 2018), the annual diameter growth (D_G) (Eq. 1) is modeled as a function of 1) maximum diameter growth (D_{Gmax}), which is influenced by tree diameter (DBH) and the atmospheric carbon dioxide (CO_2) concentration (see Table A1), and 2) environmental growth multipliers, namely growing season (April to September), temperature sum (degree days > 5°C), light availability within a stand (along a vertical light gradient), soil moisture, and nitrogen availability within a stand (Table A2):

$$D_G = D_{GMax}\ x\ (M_{Tsum}\ x\ M_L\ x\ M_{SM}\ x\ M_{NS}), \quad (1)$$

where D_{Gmax} is the maximum diameter growth, M_{Tsum} is the temperature sum multiplier, M_L is the multiplier based on light availability, M_{SM} is the soil moisture availability multiplier, and M_{NS} is the multiplier based on nitrogen supply.

If environmental conditions for growth are optimum, the multiplier = 1, and if suboptimal the multiplier is < 1 and negatively influences maximum growth (see Fig. A1). In the model, tree height (T_H) is calculated based on tree diameter and temperature sum of the growing season (under current climate) as shown in Table A3. As a result, trees at the southern site location have higher height to diameter ratios than at the northern site and vice versa (reflecting genotype differences). The probability of tree mortality is affected by stand basal area, stand density, and the maximum age of trees (Eq. 2) (see Kellomäki et al. 1992):

$$Mt = \left(\frac{\left(\frac{\left(BA\ x \left(\frac{tpa}{100} \right)^{0.7} \right)}{37} \right)}{AgeMax} \right), \quad (2)$$

where mortality probability (Mt) is a function of basal area (BA), stand density (trees ha^{-1} (tpa)), and tree age ($AgeMax$) influences the probability of death.

The resulting probability is compared against a randomly generated number to determine if the mortality event occurs each year within each iteration (i.e. *Mt* < random number between 0 and 1). A maximum age would yield on average a 2% probability of survival in any given year. Furthermore, age independent mortality will occur if there exists diameter growth below a minimum species-specific threshold for two consecutive years, in which case the probability of mortality increases to 38% in any given year.

(Fig. A1)

(Table A1)

(Table A2)

(Table A3)

(Table A4)

(Table A5)

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Figure Captions:

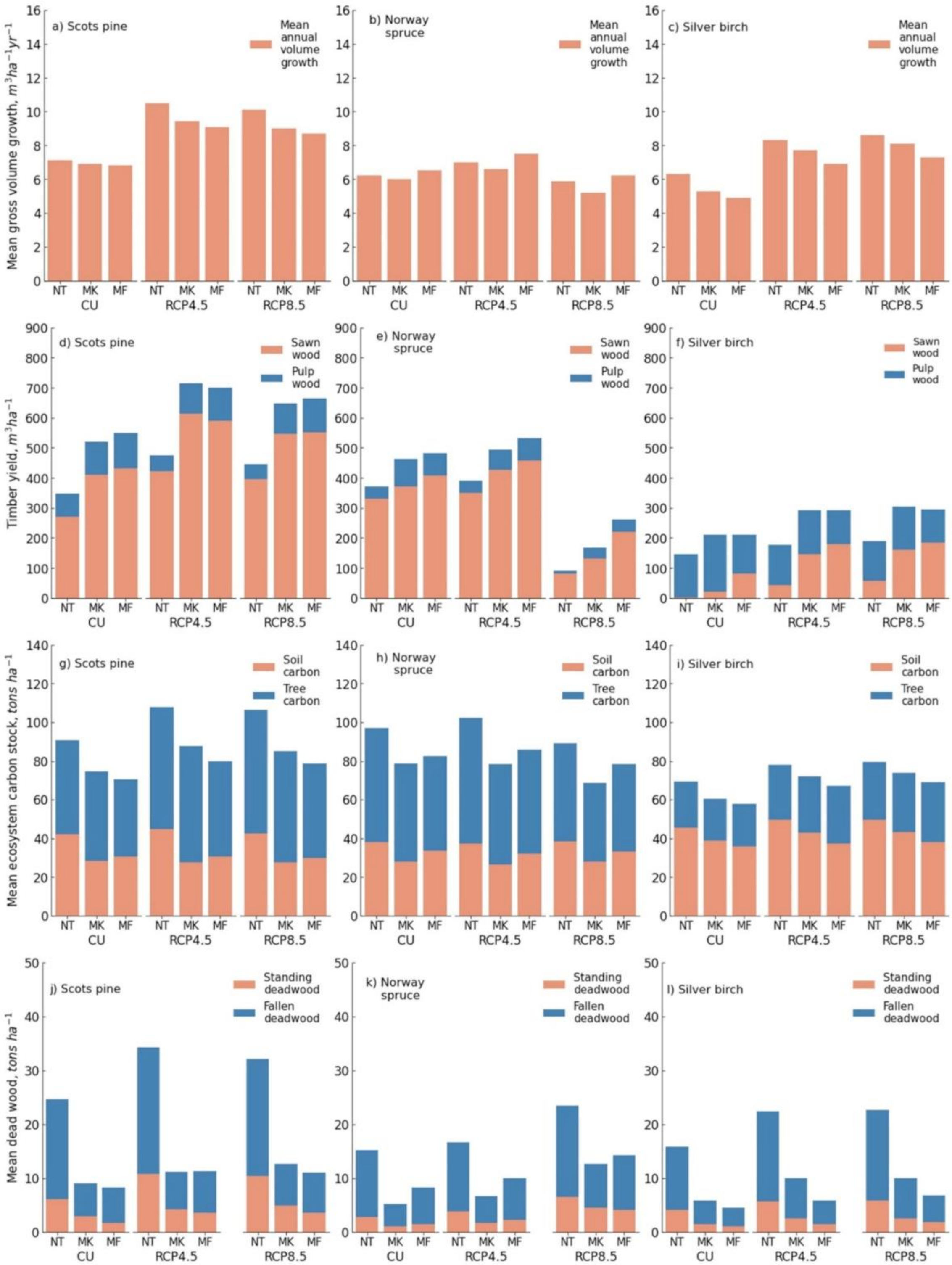
Fig 1. Mean gross annual volume growth, harvested timber yield, mean ecosystem carbon stock, and mean amount of deadwood in Scots pine, Norway spruce, and Silver birch dominate forest stands of the northern site location (Republic of Karelia) simulated under different management regimes (NT (No-thinning); MK (low intensity pre-commercial thinning); MF (high intensity pre-commercial thinning) and climates.

Fig 2. Mean gross annual volume growth, harvested timber yield, mean ecosystem carbon stock, and mean amount of deadwood in Scots pine, Norway spruce, and Silver birch dominate forest stands of the southern site location (Arkhangelsk region) under different management regimes (NT (No-thinning); MA1 (low intensity pre-commercial thinning); MA2 (medium intensity pre-commercial thinning); MF (high intensity pre-commercial thinning) and climates.

Fig 3. Percentage change in mean gross annual volume growth, harvested timber yield, mean ecosystem carbon stock and mean amount of deadwood in Scots pine, Norway spruce, and Silver birch dominate forest stands of northern site location (Republic of Karelia) under different management regimes (NT (No-thinning); MK (low intensity pre-commercial thinning); MF (high intensity pre-commercial thinning) when comparing RCP4.5 and RCP8.5 to CU (left) and when comparing management regime to MA1 (right) under CU, RCP4.5, and RCP8.5.

Fig 4. Percentage change in mean gross annual volume growth, harvested timber yield, mean ecosystem carbon stock and mean amount of deadwood in Scots pine, Norway spruce, and Silver birch dominate forest stands of southern site location (Arkhangelsk region) under different management regimes (NT (No-thinning); MA1 (low intensity pre-commercial thinning); MA2 (medium intensity pre-commercial thinning); MF (high intensity pre-commercial thinning) when comparing RCP4.5 and RCP8.5 to CU (left) and when comparing management regimes to MA1 (right) under CU, RCP4.5, and RCP8.5.

Fig A1. Diameter growth response multipliers applied within the forest ecosystem model (SIMA) and their relationship to environmental conditions of temperature, light, soil moisture, and nitrogen and for Scots pine, Norway spruce, and silver birch trees species.



a) Scots pine
b) Norway spruce
c) Silver birch
Mean annual volume growth
Mean gross volume growth, $m^3ha^{-1}yr^{-1}$
d) Scots pine
e) Norway spruce
f) Silver birch
Sawn wood
Pulp wood
Timber yield, m^3ha^{-1}
g) Scots pine
h) Norway spruce
i) Silver birch
Soil carbon
Tree carbon
Mean ecosystem carbon stock, $tons\ ha^{-1}$
j) Scots pine
k) Norway spruce
l) Silver birch
Standing deadwood
Fallen deadwood
Mean dead wood, $tons\ ha^{-1}$
NT
MK
MF
CU
RCP4.5
RCP8.5

Fig. 1

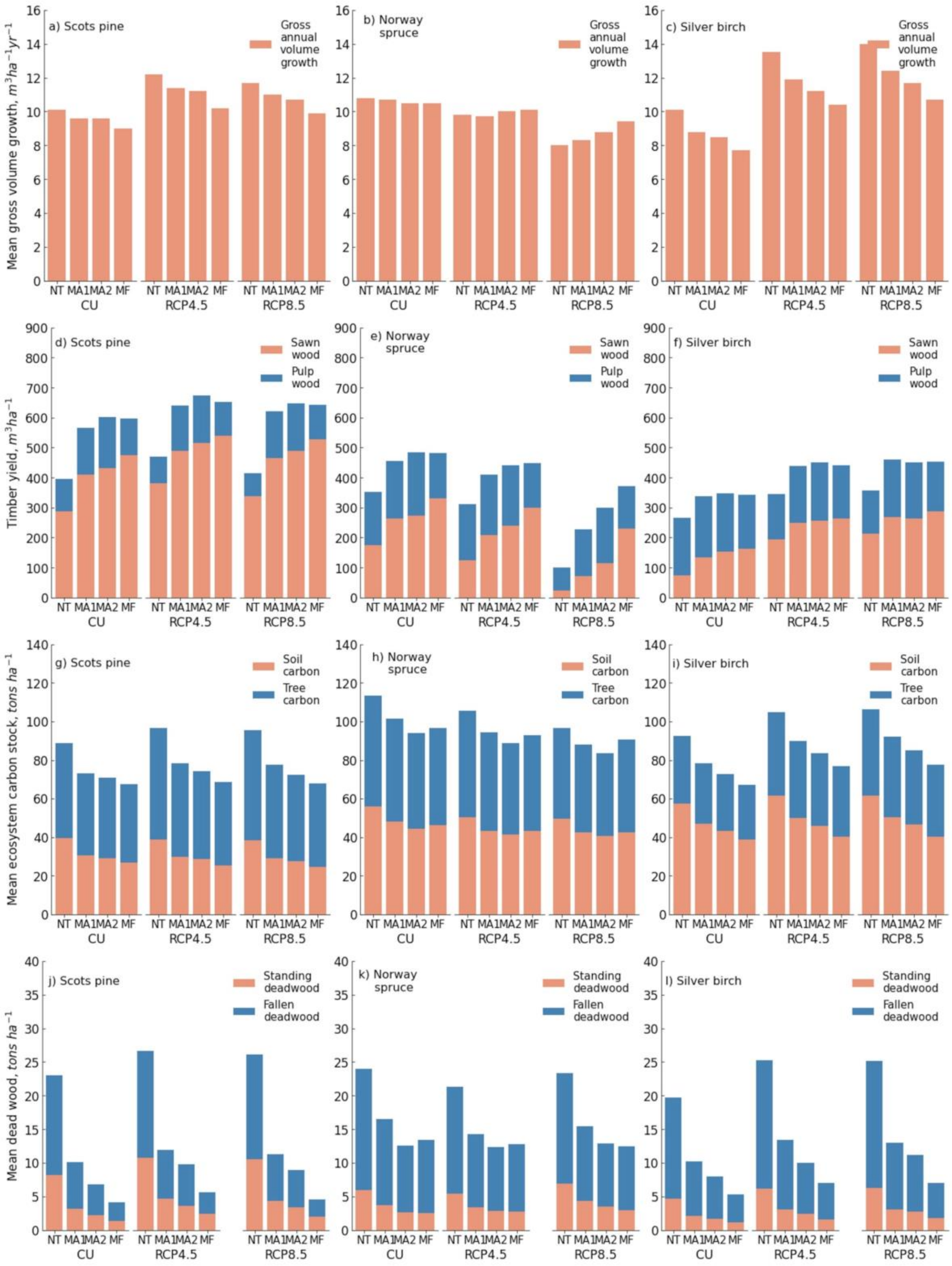

a) Scots pine
b) Norway spruce
c) Silver birch
Gross annual volume growth
Mean gross volume growth, $m^3ha^{-1}yr^{-1}$
d) Scots pine
e) Norway spruce
f) Silver birch
Sawn wood
Pulp wood
Timber yield, m^3ha^{-1}
g) Scots pine
h) Norway spruce
i) Silver birch
Soil carbon
Tree carbon
Mean ecosystem carbon stock, tons ha^{-1}
j) Scots pine
k) Norway spruce
l) Silver birch
Standing deadwood
Fallen deadwood
Mean dead wood, tons ha^{-1}
NT MA1 MA2 MF
CU
RCP4.5
RCP8.5

Fig. 2

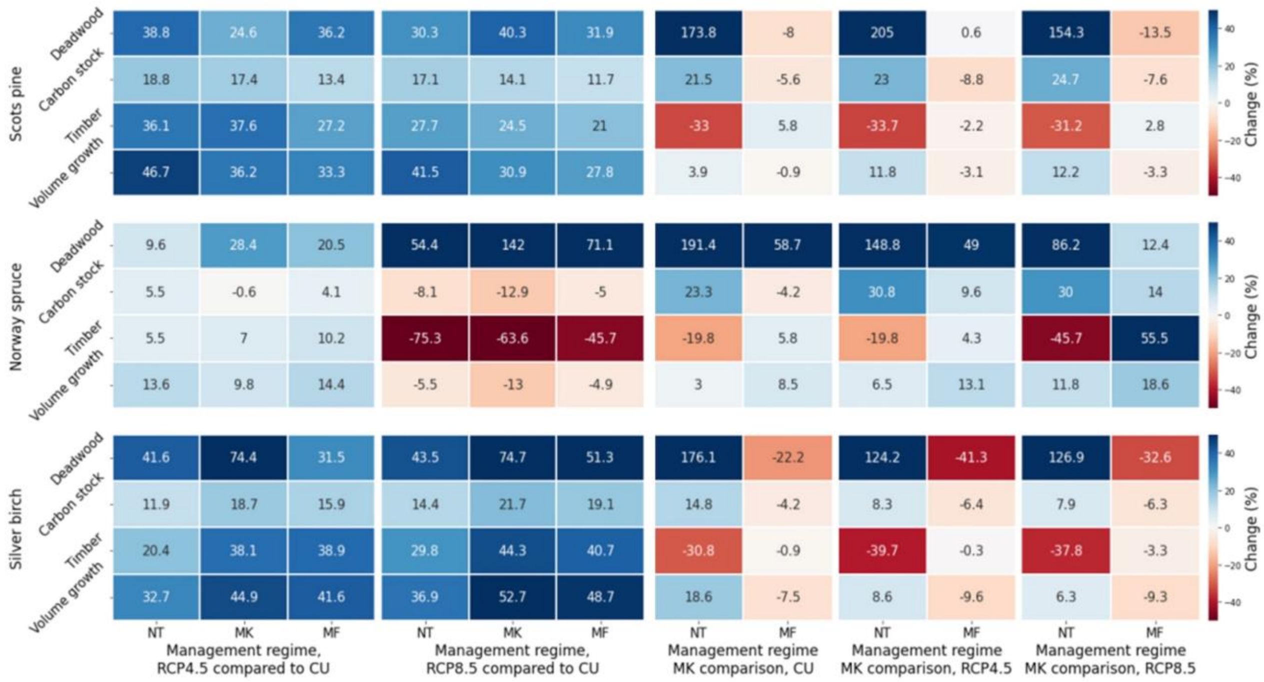

Scots pine
Deadwood 38.8 24.6 36.2 30.3 40.3 31.9 173.8 -8 205 0.6 154.3 -13.5
Carbon stock 18.8 17.4 13.4 17.1 14.1 11.7 21.5 -5.6 23 -8.8 24.7 -7.6
Timber 36.1 37.6 27.2 27.7 24.5 21 -33 5.8 -33.7 -2.2 -31.2 2.8
Volume growth 46.7 36.2 33.3 41.5 30.9 27.8 3.9 -0.9 11.8 -3.1 12.2 -3.3
Norway spruce
Deadwood 9.6 28.4 20.5 54.4 142 71.1 191.4 58.7 148.8 49 86.2 12.4
Carbon stock 5.5 -0.6 4.1 -8.1 -12.9 -5 23.3 -4.2 30.8 9.6 30 14
Timber 5.5 7 10.2 -75.3 -63.6 -45.7 -19.8 5.8 -19.8 4.3 -45.7 55.5
Volume growth 13.6 9.8 14.4 -5.5 -13 -4.9 3 8.5 6.5 13.1 11.8 18.6
Silver birch
Deadwood 41.6 74.4 31.5 43.5 74.7 51.3 176.1 -22.2 124.2 -41.3 126.9 -32.6
Carbon stock 11.9 18.7 15.9 14.4 21.7 19.1 14.8 -4.2 8.3 -6.4 7.9 -6.3
Timber 20.4 38.1 38.9 29.8 44.3 40.7 -30.8 -0.9 -39.7 -0.3 -37.8 -3.3
Volume growth 32.7 44.9 41.6 36.9 52.7 48.7 18.6 -7.5 8.6 -9.6 6.3 -9.3
NT MK MF
Management regime, RCP4.5 compared to CU
NT MK MF
Management regime, RCP8.5 compared to CU
NT MF
Management regime MK comparison, CU
NT MF
Management regime MK comparison, RCP4.5
NT MF
Management regime MK comparison, RCP8.5
Change (%)
40
20
0
-20
-40

Fig 3.

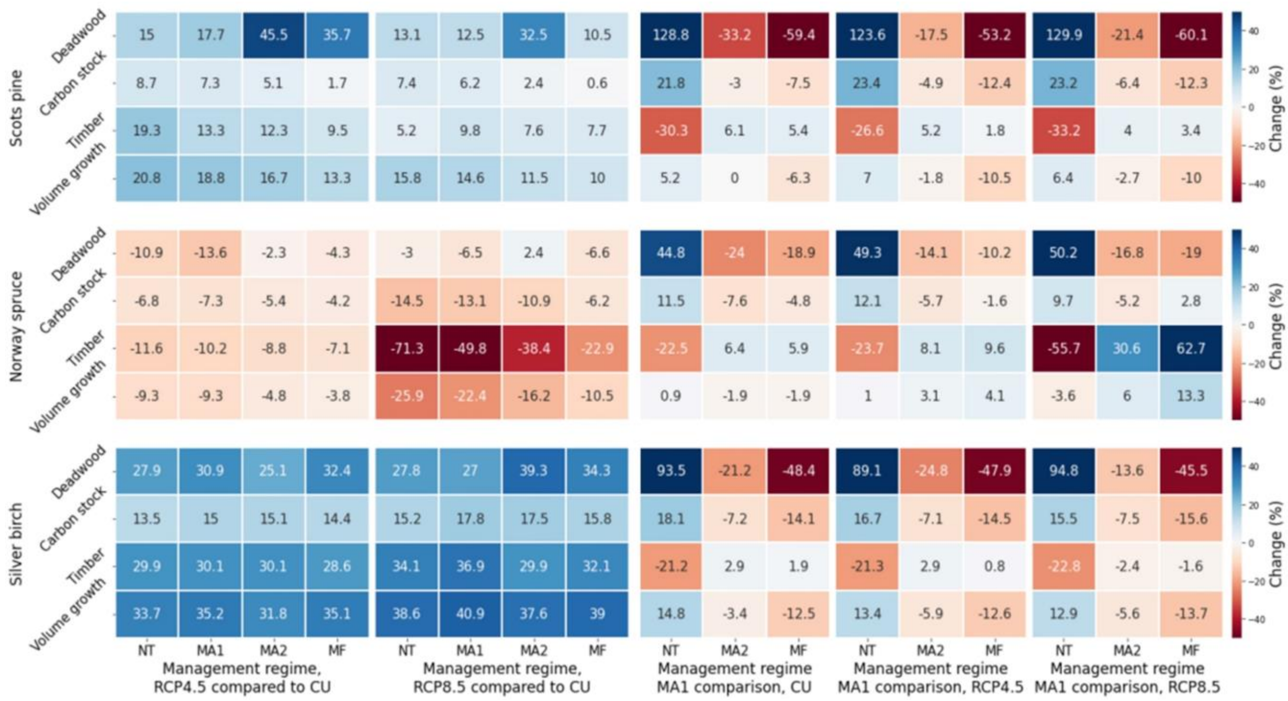

Scots pine
Deadwood 15 17.7 45.5 35.7 13.1 12.5 32.5 10.5 128.8 -33.2 -59.4 123.6 -17.5 -53.2 129.9 -21.4 -60.1
Carbon stock 8.7 7.3 5.1 1.7 7.4 6.2 2.4 0.6 21.8 -3 -7.5 23.4 -4.9 -12.4 23.2 -6.4 -12.3
Timber 19.3 13.3 12.3 9.5 5.2 9.8 7.6 7.7 -30.3 6.1 5.4 -26.6 5.2 1.8 -33.2 4 3.4
Volume growth 20.8 18.8 16.7 13.3 15.8 14.6 11.5 10 5.2 0 -6.3 7 -1.8 -10.5 6.4 -2.7 -10
Norway spruce
Deadwood -10.9 -13.6 -2.3 -4.3 -3 -6.5 2.4 -6.6 44.8 -24 -18.9 49.3 -14.1 -10.2 50.2 -16.8 -19
Carbon stock -6.8 -7.3 -5.4 -4.2 -14.5 -13.1 -10.9 -6.2 11.5 -7.6 -4.8 12.1 -5.7 -1.6 9.7 -5.2 2.8
Timber -11.6 -10.2 -8.8 -7.1 -71.3 -49.8 -38.4 -22.9 -22.5 6.4 5.9 -23.7 8.1 9.6 -55.7 30.6 62.7
Volume growth -9.3 -9.3 -4.8 -3.8 -25.9 -22.4 -16.2 -10.5 0.9 -1.9 -1.9 1 3.1 4.1 -3.6 6 13.3
Silver birch
Deadwood 27.9 30.9 25.1 32.4 27.8 27 39.3 34.3 93.5 -21.2 -48.4 89.1 -24.8 -47.9 94.8 -13.6 -45.5
Carbon stock 13.5 15 15.1 14.4 15.2 17.8 17.5 15.8 18.1 -7.2 -14.1 16.7 -7.1 -14.5 15.5 -7.5 -15.6
Timber 29.9 30.1 30.1 28.6 34.1 36.9 29.9 32.1 -21.2 2.9 1.9 -21.3 2.9 0.8 -22.8 -2.4 -1.6
Volume growth 33.7 35.2 31.8 35.1 38.6 40.9 37.6 39 14.8 -3.4 -12.5 13.4 -5.9 -12.6 12.9 -5.6 -13.7
NT MA1 MA2 MF
Management regime, RCP4.5 compared to CU
NT MA1 MA2 MF
Management regime, RCP8.5 compared to CU
NT MA2 MF
Management regime MA1 comparison, CU
NT MA2 MF
Management regime MA1 comparison, RCP4.5
NT MA2 MF
Management regime MA1 comparison, RCP8.5
Change (%)
40
20
0
-20
-40

Fig. 4

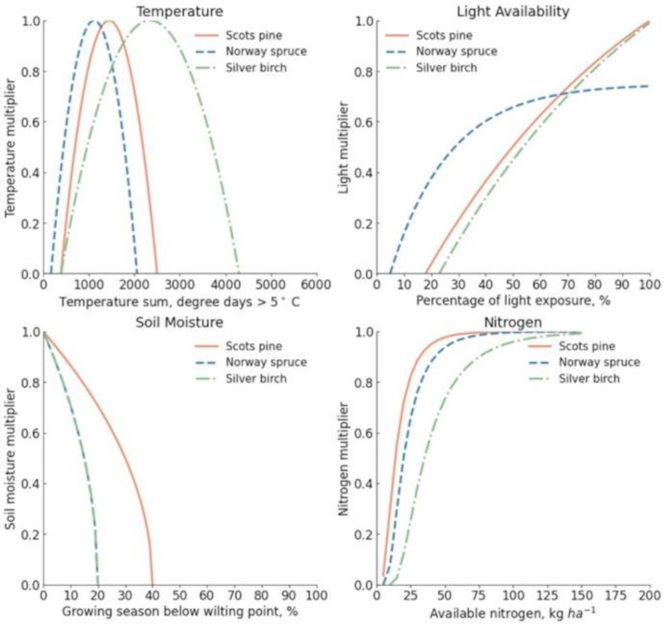

Temperature
Temperature multiplier
Temperature sum, degree days > 5 ° C
Light Availability
Light multiplier
Percentage of light exposure, %
Soil Moisture
Soil moisture multiplier
Growing season below wilting point, %
Nitrogen
Nitrogen multiplier
Available nitrogen, kg ha^{-1}
Scots pine
Norway spruce
Silver birch

Fig. A1

Tables:

Table 1. Development of temperature and precipitation by climate scenario and reference periods (mid- to end-century periods) by region.

Study site location	Climate and reference period	Mean monthly temperature, °C yr^{-1}	Mean Tsum, degree days (> 5°C April-September) yr^{-1}	Mean monthly precipitation (April-September), mm yr^{-1}	Precipitation, mm yr^{-1}
Northern	CU				
	1986-2005	2.2	1034	55.3	577
	RCP4.5				
	2046-2065	5.5	1370	60.3	654
	2080-2100	6.8	1524	59.6	675
	RCP8.5				
	2046-2065	6.1	1441	61.2	666
	2080-2100	9.6	1876	62.8	734
Southern	CU				
	1986-2005	2.0	1202	57.7	608
	RCP4.5				
	2046-2065	5.3	1559	62.7	685
	2080-2100	6.5	1725	62	706
	RCP8.5				
	2046-2065	5.8	1641	63.6	697
	2080-2100	9.3	2096	65.1	765

Table 2. Initial stand conditions for simulations of Scots pine (Sp), Norway spruce (Ns), and Silver birch (Sb) target species stands (desired primary species at final felling) by study site location.

Study site location	Target species	Age	Number of trees (stem ha^{-1}) and mean diameter (dbh, cm in parenthesis) per tree species
Northern	Scots pine	5	1,800 (1cm) Sp; 334 (4cm) Ns; 3,000 (4cm) Sb
	Norway spruce	7	668 (3cm) Ns; 377 (2cm) Sp; 379 (4cm) Sb; 875 (6cm) Ea*
	Silver birch	10	7,000 (2cm) Sb; 1,200 (1cm) Ns; 600 (1cm) Sp
Southern	Scots pine	5	7,800 (1cm) *Sp*; 1,600 (2cm) *Ns*; 9,200 (1cm) *Sb*
	Norway spruce	14	7,300 (4cm) *Ns*; 3,000 (4cm) *Sb*; 300 (6cm) *Ea**
	Silver birch	5	6,900 (2cm) *Sb*; 1,400 (2cm) *Ea*; 1,500 (1cm) *Ea**

*Eurasian aspen (*Populus tremula* (L.))

Table 3. Stand management alternatives (MA) and their pre-commercial and commercial thinning treatments (i.e. age, removal percentage (in parenthesis)), and rotation lengths (Rot) used in target species stands at each site location. In pre-commercial thinning, removals are based on density of stems ha^{-1} and for commercial thinning, stand basal area. Variation in basal area removal percentages under MF is due to influence of climate on growth, as thinning thresholds were contingent on dominant height versus basal area relationships, while with MK, MA1, and MA2 thinning occurred at fixed stand ages.

			Pre-commercial thinning		Commercial thinning			Final felling
Site location	Target species	MA	1st, age (r %)	2nd, age (r %)	1st, age (r %)	2nd, age (r %)	3rd, age (r %)	Rot, age
Northern	Scots pine	NT	-	-	-	-	-	101
		MK	11(45)	21(45)	41(35)	61(35)		101
		MF	5(60)	-	40(31-32)	58-61(42-43)	75-81(43-44)	101
	Norway spruce	NT	-	-	-	-	-	97
		MK	11(40)	21(40)	41(35)	61(23)	-	97
		MF	5(70)	-	44(42)	67-69(40-43)	-	97
	Silver birch	NT	-	-	-	-	-	61
		MK	10(25)	20(25)	30(25)	50(30)	-	61
		MF	10(81)	-	40(42-43)	-	-	61
Southern	Scots pine	NT	-	-	-	-	-	81
		MA1	11(45)	21(45)	41(35)	61(35)	-	81
		MA2	5(73)	15(25)	35(37)	55(50)	-	81
		MF	5(89)	-	24(25-35)	48(38-39)	63-65(44-45)	81
	Norway spruce	NT	-	-	-	-	-	81
		MA1	-	21(35)	41(25)	61(23)	-	81
		MA2	-	21(47)	41(40)	61(40)	-	81
		MF	14(81)	-	39-40(29-30)	61(32-34)	-	81
	Silver birch	NT	-	-	-	-	-	61
		MA1	5(25)	15(25)	25(25)	45(30)	-	61
		MA2	5(55)	15(10)	30(30)	45(30)	-	61
		MF	5(81)	-	30(31-32)	42-45(38-39)	-	61

Table A1. Maximum diameter growth (D_{GMax}, cm year^{-1}) parameters by tree species for Finnish conditions based on Kellomäki et al. (2008; 2018) and as calibrated for Russian conditions in a study of Ulianova (2018), where a, b, and c are location specific parameters, and *DBH* (cm year^{-1}) is diameter at breast height.

Maximum diameter growth eq.

$$D_{GMax} = \exp\left(a - \frac{b}{0.01 \times CO_2}\right) \times DBH \times e^{c \times DBH}$$

Model	Species	Parameters a	b	c
Original	Scots pine	-1.307	1.643	-0.0719
	Norway spruce	-1.307	1.643	-0.0562
	Silver birch	-1.307	1.643	-0.0706
Calibrated	Scots pine	-1.307	1.643	-0.0590
	Norway spruce	-1.307	1.643	-0.0500
	Silver birch	-1.307	1.643	-0.0950

Table A2. Growth multipliers contributing to diameter growth calculation in equation (1).

Growth Multiplier	Growth multiplier function descriptions and equations
Temperature sum, M_{TSUM}	Mean annual (*Tsum*), minimum (*MinT*), and maximum (*MaxT*) temperature sums (degree days > 5°C from April to September) are represented by species-specific parabolas as a function of temperature and define the geographic temperature distribution by tree species for any given year (Kellomäki et al. 2008, 2018). Species-specific *MinT* and *MaxT* have been adapted to the model based on Kienast (1987) and Nikolov and Helmisaari (1992).
	$M_{TSUM} = \frac{(4 \times (Tsum - MinT) \times (MaxT - Tsum))}{(MaxT - MinT)^2}$
Light availability, M_L	Light availability limits tree specific growth, as the height and foliage mass of each tree, cumulative foliage mass of trees taller than any given tree, and the proportion of light (*LR*) penetrating through the foliage influence available light for individual tree growth, where A1,…,A3 are location specific parameters (Kellomäki et al. 1992).
	$M_L = A1 \times \left(1 - \exp\left(A2 \times \left(\frac{LR}{100 - A3}\right)\right)\right)$
Soil moisture, M_{SM}	The ratio of dry days (*Wt*) below the wilting point within the growing season (GS_{days}, April-September) and species-specific drought tolerances (D_T) determine growth response to moisture, while the field capacity and wilting point define the availability of soil moisture for growth on different soil and site types as a function of precipitation and evaporation (Kellomäki et al. 1992).
	$M_{SM} = \left(\left(\frac{D_T \times GS_{days} - Wt}{D_T \times GS_{days}}\right)\right)^{0.5}$
Nitrogen availability, M_{NS}	Nitrogen supply (N_S) is affected by nitrogen content of foliage (*NCon*), where CM1,…,CM5 are location specific parameters. Nitrogen concentration in foliage is related to the available soil nitrogen (nitrate and ammonium) for tree growth, as litter and mortality of trees transfer carbon and nitrogen into the soil, where decomposition of litter and soil organic matter releases nitrogen for tree growth (Kellomäki et al. 1992).
	$M_{NS} = \left(1 - \left(\frac{CM1}{NCon - 1}\right) \times \left(\frac{CM5}{CM4}\right)\right)^{\left(\frac{CM5}{CM4}\right) \times \left(\frac{CM1}{NCon}\right)}$ $NCon = CM1 \times (1 - 10^{(-CM3 \times (-170 + 4 \times N_S + CM2))})$

Parameters	Scots pine	Norway spruce	Silver birch
MinT	390	170	390
MaxT	2500	2060	4300
A1	1.65	0.75	1.7
A2	-1.136	-4.64	-1.136
A3	0.18	0.5	0.23
D_T	0.4	0.2	0.2
CM1	1.77	1.77	2.93
CM2	175	171	172
CM3	0.0036	0.0028	0.0016
CM4	0.07	0.06	0.25
CM5	0.004	0.006	0.029

Table A3. Tree height (T_H) model parameters by site and tree species as derived from Finnish Forest Inventory data (Kellomäki et al. 2008) and as calibrated for Russian conditions in a study of Ulianova (2018), where T_{sum} is the temperature sum of the growing season (under current climate), *DBH* is diameter at breast height, and a, b, and c are location specific parameters.

Height model eq.

$$T_H = \left[\frac{T_{sum}}{1000}\right]^C \times \left[1.3 + \frac{DBH^2}{a + b \times DBH^2}\right]$$

Model	Species	Parameters		
		a	b	c
Original	Scots pine	2.117	0.166	0.435
	Norway spruce	2.137	0.159	0.669
	Silver birch	1.669	0.169	0.730
Calibrated	Scots pine	2.117	0.166	2.0856
	Norway spruce	2.137	0.159	2.94316
	Silver birch	1.669	0.169	3.13986

Table A4. Growth and yield table variables by tree species and stand age used in a study by Ulianova (2018) to calibrate SIMA model for Russian sites.

Species	Stand age, years	Height, m	Diameter at breast height (DBH), cm	Density, trees ha^{-1}	Basal area, m^2 ha^{-1}	Volume, m^3 ha^{-1}
Scots pine	20	7.2	7.2	4,610	18.9	72
	30	10.6	10.8	2,729	25.2	136
	40	14	14.2	1911	30.1	208
	50	16.8	17.5	1378	33.2	269
	60	19.2	20.8	1050	35.7	321
	70	21.1	23.5	862	37.4	367
	80	22.6	25.6	757	39	409
	90	23.8	28	657	40.5	445
	100	24.7	30.3	580	41.8	476
	110	25.4	32	532	42.8	501
	120	26	33.6	489	43.4	521
	130	26.5	35	456	43.9	536
	140	26.9	36	432	44	546
Norway spruce	20	6.8	6.8	6,060	22	90
	30	10.4	9.1	4,081	26.2	150
	40	14.4	12.6	2,213	27.6	215
	50	16	16.5	1,406	30.1	281
	60	20.7	20.2	1,012	32.4	342
	70	23	23.4	793	34.1	396
	80	24.6	26.2	668	36	444
	90	25.9	28.4	592	37.5	486
	100	27	30.1	546	38.9	525
	110	27.9	31.7	517	40.8	569
	120	28.6	33	492	42.3	594
Silver birch	10	5.7	4	9,524	12	36
	20	11.4	9	2,850	18.2	100
	30	15.9	12.4	1,926	23.3	170
	40	19.5	18	1,032	26.2	230
	50	22.4	21	807	28	277
	60	24.4	23.5	678	29.4	320
	70	25.4	25.3	612	30.6	345
	80	26.2	26.5	572	31.6	370

Table A5. Mean temperature sum, days below wilting point, and frequency of >75% of maximum Tsum and D_T (% growing season below wilting point) values assuming 90-year simulation period by location and climate.

Site location	Climate	Mean Tsum, degree days	Mean days below wilting point	Tsum > 75% of Max Tsum, years			D_T > 75% of Max D_T, years		
				Scots pine	Norway spruce	Silver birch	Scots pine	Norway spruce	Silver birch
Northern	CU	1046	0.00	0	0	0	0	0	0
	RCP4.5	1353	0.01	0	9	0	0	0	0
	RCP8.5	1492	0.03	12	39	0	0	0	0
Southern	CU	1208	0.00	0	0	0	0	0	0
	RCP4.5	1540	0.04	0	51	0	0	0	0
	RCP8.5	1690	0.26	29	59	0	0	0	0