Effects of using certain tree species in forest regeneration on volume growth, timber yield, and carbon stock of boreal forests in Finland under different CMIP5 projections

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Abstract

We studied how the use of certain tree species in forest regeneration affected the volume growth, timber yield, and carbon stock of boreal forests in Finland under the current climate (1981-2010) and recent-generation global climate model (GCM) predictions (i.e., multi-model means and individual GCMs of CMIP5), using the representative concentration pathways RCP4.5 and RCP8.5 over the period 2010–2099. Forest ecosystem model simulations were conducted on upland national forest inventory plots throughout Finland. In a baseline management regime, forest regeneration was performed by planting the same tree species that was dominant before the final cut. In alternative management regimes, either Scots pine, Norway spruce or silver birch were planted on medium-fertility sites. Other management actions over rotation were done as in a baseline management. Compared to baseline management, an increased planting of birch resulted in relative sense highest increase in the volume growth, timber yield, and carbon stock in forests in the south, especially under severe climate projections (e.g., multi-model mean RCP8.5, and GCMs such as HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5). This situation was opposite for Norway spruce. In the north, the volume growth, timber yield, and carbon stock of forests increased the most under severe climate projections (e.g., multi-model mean RCP8.5 and CNRM-CM5 RCP8.5), regardless of tree species preference. The magnitude of the climate change impacts depended largely on the geographical region and the severity of the climate projection. Increasing the cultivation of birch and Scots pine, as opposed to Norway spruce, could be recommended for the south. In the north, all three species could be cultivated, regardless of the severity of climate change.

Keywords: Carbon stock, gap-type forest ecosystem model, forest management, RCP4.5, RCP8.5, timber yield, tree species preference, volume growth.

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1. Introduction

The gradually changing climate is expected to increase the volume growth of boreal forests in Nordic countries (Kellomäki et al. 2008; Poudel et al. 2011, 2012). This is due to longer growing seasons and the increased decomposition of soil organic matter, which increases the supply of available nitrogen for growth under a warming climate (Saxe et al. 2001; Hyvönen et al. 2007). Likewise, the increase in atmospheric CO_2 concentration will generally enhance forest growth (Peltola et al. 2002; Ellsworth et al. 2012). Consequently, forest carbon stock and timber yield may increase under a changing climate (Kellomäki et al. 2008; Lindner et al. 2010; Poudel et al. 2011, 2012). Severe climate warming, and an associated increase in drought conditions, however, may make the current growing conditions suboptimal for some tree species, but more optimal for others (e.g., Allen et al. 2010; Lindner et al. 2010).

In Finland, the most important commercial tree species are Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and silver birch (*Betula pendula*). Scots pine and Norway spruce account for 45% and 31% of the total volume of growing stock, respectively, and birches (*Betula* spp.) and other broadleaves 24% (Finnish Forest Research Institute 2014). During 2009–2013, the average annual regeneration area was around 125,000 hectares, of which 65% was planted with Norway spruce, Scots pine, and silver birch, 20% was seeded by Scots pine, and 15% was naturally regenerated using mainly seed tree cutting in Scots pine (Finnish Forest Research Institute 2014). Based on Finnish management recommendations for practical forestry (Äijälä et al. 2014), it is suggested that Norway spruce and silver birch are regenerated mainly on sites of medium and higher fertility, and Scots pine on sites of medium and lower fertility.

Currently, however, the share of Norway spruce in the total planting area of Finland is very high, at about 70%, whereas it was 25–30% in the early 1990s. Norway spruce is nowadays also regenerated on less fertile sites than recommended because of moose browsing and other mammal damage to young Scots pine and birch stands (Finnish Forest Research Institute 2014). Under a warming climate, with an increase in droughts, the growth of Norway spruce is expected to suffer in southern Finland on medium or less fertile sites with low water-holding capacities (Mäkinen et al. 2001; Jyske et al. 2010; Torssonen et al. 2015). Thus, extensive cultivation of Norway spruce may decrease carbon sequestration, volume growth, and wood production in Finnish forests under warming climatic conditions (Kellomäki et al. 2008, 2018).

Different kinds of adaptive forest management measures may be needed, and they may depend largely on geographical region and degree of climate change (Kellomäki et al. 2008; Kolström et al. 2011). The development of forest resources is also affected by environmental conditions (climate, site), current forest structure (age, species), and forest management (Kellomäki et al. 2008; Poudel et al. 2012). Their interactive effects can be studied, at stand and regional level, by applying forest ecosystem models, together with up-to-date information on current forest resources, and different management regimes and climate change projections (see, e.g., Briceno-Elizondo et al. 2006a, b;

Garcia-Gonzalo et al. 2007a, b; Kärkkäinen et al. 2008; Kellomäki et al. 2008; Matala et al. 2009; Torssonen et al. 2015). Such model-based studies could provide the necessary support for the sustainable management and utilization of forest resources under changing climate, considering different ecosystem services. This is crucial, as large trade-offs may occur for the production of different ecosystem services (Seidl et al. 2007; Kellomäki et al. 2008; Matala et al. 2009; Kindermann et al. 2013; Seidl and Lexer 2013; Triviño et al. 2015; Bottaloco et al. 2016; ALRahaleh et al. 2017).

Large uncertainties still exist in projections of climate change (Ruosteenoja et al. 2016). Compared to the current (1981–2010) climate in Finland, the mean temperature during the potential growing season, in April–September, may increase by 3–5°C, and mean precipitation by 7–14%, depending on the geographical region, and based on the multi-model mean values of 28 recent-generation (Coupled Model Intercomparison Project Phase 5, CMIP5) global climate model (GCM) projections, under moderate and severe representative concentration pathways RCP4.5 and RCP8.5 forcing scenarios (Ruosteenoja et al. 2016). Concurrently, atmospheric CO_2 concentrations are expected to increase from the current value of 360 ppm to 536 ppm (RCP4.5) and 807 ppm (RCP8.5) during the period 2070–2099. Compared to the previous CMIP3 database (Special Report on Emissions Scenarios, SRES), the recent-generation GCM projections predict greater increases in temperature, but marginal changes in precipitation (Ruosteenoja et al. 2016). Some individual GCMs, such as GFDL-CM3 RCP8.5 and HadGEM2-ES RCP8.5, predict, depending on geographical region, up to a 6–7°C increase in temperature during the potential growing season by 2070–2099. At the same time, they predict a slight to moderate increase in precipitation in the north, but only a slight increase (GFDL-CM3 RCP8.5) or a decrease (HadGEM2-ES RCP8.5) in precipitation in the south.

Most previous climate impact studies for Finland, either at the stand or regional level, have employed the SRES (e.g., SRES A1B of CMIP3), or other scenarios (Kellomäki et al. 2008; Briceno-Elizondo et al. 2006a, b; Garcia-Gonzalo et al. 2007a, b; Torssonen et al. 2015). Only a few recent impact studies have employed, either at the stand or regional level, multi-model mean climate projections (e.g., ALRahahleh et al. 2017, 2018; Kellomäki et al. 2018), or individual GCM projections (e.g., Lehtonen et al. 2016a, b; ALRahahleh et al. 2017; Ruosteenoja et al. 2018) of the CMIP5 database, under different RCP forcing scenarios.

In this work, we studied how the use of certain tree species in forest regeneration affected the volume growth, timber yield and carbon stock of boreal upland forests in Finland under the current climate (1981–2010), and recent-generation (CMIP5) GCM predictions, using the representative concentration pathways RCP4.5 and RCP8.5 over the period 2010–2099. The forest ecosystem model simulations were conducted on upland National Forest Inventory (NFI10) plots, located throughout Finland. We used in the simulations both the multi-model mean values of 28 individual GCMs under RCP4.5 and RCP8.5, and climate data from 10 selected individual GCMs (four under RCP4.5 and six under RCP8.5). Under baseline management, forest regeneration was performed by planting the same tree species that was dominant before the final cut. Under alternative management regimes, either Scots pine, Norway spruce or silver birch were planted, on medium-fertility sites. Other management actions over rotation were done as in a baseline management.

2. Material and methods

2.1 Outline of the forest ecosystem model (SIMA)

We used a gap-type forest ecosystem model (SIMA) (Kellomäki et al. 2005, 2008, 2018) to simulate the regeneration, growth and mortality of upland (mineral) forest sites throughout Finland. In the model, optimal conditions refer to growth and/or regeneration under no shade, and with no limitations in soil moisture or nitrogen supply. The environmental conditions are linked in the model by multipliers of the demographic processes, that is, $G = G_0 \times M_1, \ldots, M_n$, where G is growth, G_0 is growth under optimal conditions, and $M_1, \ldots, M_n$ are multipliers representing the temperature sum (+5^{o}C threshold), prevailing light conditions, and availability of soil water and nitrogen. In addition, growth is affected by atmospheric CO_2 concentrations, nitrogen deposition, and tree maturity (diameter at breast height, 1.3 m above the ground) (**Fig. 1**). The diameter at breast height is used to calculate tree height, and the mass of tree organs (foliage, branches, stem, and roots).

Fig. 1.

In the model, the species-specific growth response to the temperature sum is modeled based on downwards opening symmetric parabola, with species-specific minimum, optimum, and maximum temperature sums for growth. The minimum, optimum, and maximum temperature sums for growth are the smallest in Norway spruce (370, 1,215, and 2,060 d.d.), followed by Scots pine (390, 1,445, and 2,500 d.d.), and silver birch (390, 2,360, and 4,330 d.d.) (Kienast 1987; Nikolov and Helmisaari 1992; Kellomäki et al. 2008). Based on this, the prevailing temperature sum conditions are, under the current climate, at near optimum in southern Finland (period 1981–2010; Tsum 1,200–1,400 d.d.), especially for Norway spruce, but also for Scots pine, and unlike for birch. In northern Finland (Tsum <1,000 d.d.), the relatively short growing season, and low temperatures during the growing season, currently limit forest growth, regardless of tree species. The effects of a temperature increase on growth, under different climate change projections, are calculated based on monthly changes in the temperature sum, compared to the temperature sum of current climate during the potential growing season (April–September), to meet the prevailing light conditions.

Field capacity and wilting point define the soil moisture available for growth on different soil and site types as a function of precipitation and evaporation. The initial amount of soil organic matter (and carbon) and nitrogen available for growth are defined based on the site fertility type and regional temperature sum of the current climate (see Kellomäki et al. 2005, 2008). The amount of soil organic matter (and carbon) and nitrogen available for growth are also affected by the input of litter and deadwood to the soil layer, and their decay.

To initialize the simulations, the properties of a tree stand were described in terms of tree species, including the number of trees per hectare in each diameter class. In model simulations, management control includes artificial regeneration (planting) with the desired spacing and tree species, control of stand density in the tending of a seedling stand and in thinnings (including naturally born seedlings), nitrogen fertilization, and the final cut. The model simulations were performed with a time step of one year, and they were carried out on an area of 100 m^2, based on the Monte Carlo technique (i.e., certain events, such as the births and deaths of trees, are stochastic events). The observed long-term mean in Finland for atmospheric nitrogen deposition (10 kg N ha^{-1}) was used in the simulations

(Järvinen and Vänni 1994; Kellomäki et al. 2005). The mean values of 20 iterations of each output variable were used in the data analyses, following previous work by ALRahahleh et al. (2017).

The SIMA model has been discussed in detail previously by Kellomäki et al. (2005, 2008, 2018). A previous model validation by Kellomäki et al. (2008) showed good agreement between the simulated and measured mean annual volume growth of the main Finnish tree species (Scots pine, Norway spruce, and birch) on NFI plots throughout Finland, for different Forest Centre Units. The model comparison by Routa et al. (2011) also indicated a good agreement between simulations using the SIMA model and the statistical growth and yield model, MOTTI (Hynynen et al. 2002), for the mean annual volume growth of Norway spruce and Scots pine stands on sites of medium fertility, in different locations throughout Finland.

2.2 Forest stand and climate input data, and management activities used in simulations

The initial stand and site characteristics used in the simulations were based on the NFI (NFI10) of Finland. We used forest inventory data from one randomly selected sample plot for every permanent cluster of sample plots on upland forest land assigned to timber production. The average distance between the clusters of sample plots is 6×6 km throughout Finland, excluding northernmost Finland (Forest Centre Unit 13), where it is 10 × 10 km (Korhonen 2016). Our data included 2,642 sample plots, of which 1,388 plots were on medium-fertile mesic sites (*Myrtillus* type, MT), 529 on fertile herb-rich sites (*Oxalis myrtillus* type) or more fertile sites, 641 on less fertile sub-xeric sites (*Vaccinium* type), and 84 on poorer dryish sites (*Cladonia* type).

The current climate data were based on measurements by the Finnish Meteorological Institute for temperature and precipitation over the period 1981–2010. In addition to the current climate, we used both the multi-model mean values of 28 individual GCMs under RCP4.5 and RCP8.5, and climate data for 10 individual GCMs (four under RCP4.5 and six under RCP8.5), which were downloaded from the CMIP5 database by the Finnish Meteorological Institute (**Table 1**; see also Ruosteenoja et al. 2016). We expected that the use of 10 selected GCMs would provide a good representation of the overall variability in the full ensemble of CMIP5 projections under the RCP4.5 and RCP8.5 forcing scenarios. These climate datasets comprise the projected change in monthly mean temperatures and precipitation for 2010–2099.

We selected 10 GCMs based on their ability to simulate the temperature and precipitation of the current climate (1981–2010) (see e.g., Lehtonen et al. 2016a, b; Ruosteenoja et al. 2016). However, the predicted values for daily mean temperature and precipitation in the individual GCMs (either high or low, in relation to the observed data) still needed to be bias-corrected, which was done using quantile mapping. This method has previously been found to be among the best-performing empirical bias-correction methods for temperature and precipitation throughout the probability distribution (see Räisänen et al. 2013; Räty et al. 2014). As a result of bias-correction, the predicted cumulative probability distributions of simulated temperature and precipitation time-series fit well with the current climate. Both the observational and climate change data were also interpolated by the Finnish Meteorological Institute onto a 10 x 10 km grid throughout Finland, using the kriging with external drift (KED) method (Venäläinen et al. 2005; Aalto et al. 2013, 2016).

The mean temperature and precipitation during the potential growing season (April–September) under the current climate (1981–2010) is 11.0°C and 296 mm, respectively, in southern Finland (old Forest Centre Units 1–6), and 8.3°C and 286 mm in northern Finland (old Forest Centre Units 10–13). Compared to the current climate, the mean temperature in April–September may increase by 3–5°C, and mean precipitation by 7–14%, depending on the geographical region, and based on the multi-model mean values of 28 GCMs under RCP4.5 and RCP8.5 forcing scenarios (Ruosteenoja et al. 2016). Concurrently, the atmospheric CO_2 concentrations are expected to increase from the current value of 360 ppm to 536 and 807 ppm during the period 2070–2099 (**Table 1**). Some GCMs, such as GFDL-CM3 RCP8.5, predict up to a 6.3–7°C increase in temperature, and 14–26% increase in precipitation (April–September) by 2070–2099, depending on the region. Also, HadGEM2-ES RCP8.5 predicts up to a 6.1°C increase in temperature, but, depending on the region, either a 9% decrease (in the south) or a 7% increase (in the north) in precipitation. As a comparison, for example, CNRM-CM5 RCP8.5 predicts up to a 3.7–3.9°C increase in temperature, and a 19–24% increase in precipitation over the same period, depending on the region.

Table 1.

In forest ecosystem model simulations, under baseline management, forests were regenerated by planting the same tree species that was dominant before the final cut. Under alternative management regimes, either Scots pine, Norway spruce or silver birch were planted on medium fertile (MT) sites. Other management actions over rotation were done as in a baseline management (see **Table 2**). In addition to planting, Scots pine, Norway spruce, and birch seedlings were also expected to regenerate naturally at all sites (see Kellomäki and Väisänen 1995; Kellomäki et al. 1997). Tending of the seedling stands was carried out, if necessary, before the first commercial thinning, by removing mostly smaller or suppressed trees. Otherwise, in all simulations, we used the region, site and tree species-specific Finnish management recommendations as a basis for the timing and intensity of thinnings, and the timing of final felling (see Äijälä et al. 2014).

We used, on average, a 13-year delay in thinnings and final fellings, compared to the management recommendations, because they are often delayed, compared to management recommendations (see Finnish Forest Research Institute 2014). Strictly following the thinning rules would have led to unrealistically high timber yields and large reductions in the volume of growing stock at the beginning of the simulation. Furthermore, we left parts of the forest plots from central to northern Finland outside management, unlike in southern Finland, where the current forest conservation area is very low, at around 2% (Finnish Forest Research Institute 2014). As a result, the predicted stem volume growth, volume of growing stock, and timber yield for the first 30-year simulation period (2010–2039) under the current climate were in good agreement with the forest statistics for the period 2004–2009 (Finnish Forest Research Institute 2014).

Table 2.

2.3 Data analyses

For each simulation case, the mean annual stem volume growth (m^3 ha^{-1} a^{-1}), timber yield (m^3 ha^{-1} a^{-1}), and forest ecosystem carbon stock (in trees and soil, Mg ha^{-1}) were calculated for each 30-year period. We also analyzed development of the proportion of each tree species (% stem volume) of the growing stock. Based on these data, we studied how the increase in the planting of certain tree species in forest regeneration on medium-fertile upland sites (MT) affected the development of tree species proportions, volume growth, timber yield, and carbon stock of forests from southern (old Forest Centre Units 1–6) to central (Units 7–10) and northern (Units 11–13) Finland, under changing climatic conditions for the periods 2010–2039, 2040–2069, and 2070–2099 (further information for regions of old Forest Centre Units, see Finnish Forest Research Institute 2014). The effects of climate change were compared to the current climate under the same management regime, and the effects of management (i.e., tree species preference in forest regeneration) to the baseline management under the same climate projection. Below, we report the findings in detail, based on the use of multi-model climate data, and climate data for selected individual GCMs, such as CNRM-CM5 RCP8.5, HadGEM2-ES RCP8.5, and GFDL-CM3 RCP8.5, which show the largest variability, compared to the multi-model mean results. Results for all 10 GCMs are shown in detail in the tables in the Appendix.

3. Results

3.1 Proportion of tree species

Under the current climate with baseline management, the proportion of birch decreased from the first to the last 30-year period in the south from 18% to 9%, and in the north from 13% to 9%. At the same time, the proportion of Scots pine increased from 42% to 48% in the south, and decreased in the north from 65% to 62%. The proportion of Norway spruce increased both in the north, from 22% to 29%, and in the south, from 40% to 43% (**Fig. 2**). When the planting of Scots pine was increased, its proportion increased largely, and was in the south up to 72%, and in the north up to 75%, in the last 30-year period. Correspondingly, when the plantings of Norway spruce and birch were increased, their proportions increased also, and were in the south up to 67% and 35%, and in the north up to 47% and 27%, in the last 30-year period, respectively.

Under the multi-model mean climate projections of RCP4.5 and RCP8.5 forcing scenarios (i.e. multi-model means of RCP4.5 and RCP8.5), and baseline management, the proportion of Scots pine, in the last 30-year period, ranged in the south from 53% to 61%, and in the north from 68% to 70% (**Fig. 2**). At the same time, the corresponding range for Norway spruce was, in the south, 18–35% (the smallest under RCP8.5), and, in the north, 23–25%. The corresponding range for birch was 11–21 % in the south, and 6–7% in the north. When the planting of Scots pine increased, its proportion ranged from 75% to 81% in the south, and from 79% to 80% in the north. When the planting of Norway spruce increased, its corresponding range was 38–61% (the smallest under RCP8.5) in the south, and 43–44% in the north. However, when the planting of birch was increased, its corresponding range was 48–63% in the south, and 21–22% in the north.

Conversely, the proportions of tree species under individual GCM projections, such as CNRM 8.5, were equal to, or lay between, those of the multi-model means of RCP4.5 and RCP8.5 in the south and north, regardless of the tree species and their preference in planting (**Fig. 2**). Under the individual GCM projections, such as HadGEM2 8.5 and GFDL 8.5, the proportion of Norway spruce decreased drastically, whereas the proportion of birch increased in the south and north, compared to the multi-model means of RCP4.5 and RCP8.5, regardless of tree species preference. The proportion of Scots pine under baseline management was also higher under HadGEM2 8.5 than under the multi-model mean of RCP8.5 in the south, as opposed to that under GFDL 8.5. In the north, the proportion of Scots pine and birch increased under HadGEM2 8.5 and GFDL 8.5, compared to the multi-model mean of RCP8.5, regardless of tree species preference (**Fig. 2**). The preference for a certain tree species in forest regeneration affected the tree species composition in the long term more than did the climate projection.

Fig. 2

3.2 Volume growth

Under the current climate, with baseline management, the volume growth increased in the south from 5.8 to 7.0 m^3 ha^{-1} a^{-1}, and in the north from 2.8 to 3.3 m^3 ha^{-1} a^{-1}, from the first to last 30-year period (**Figs. 3 and 4**). The preference of different tree species in forest regeneration affected only marginally the first 30-year period of volume growth, regardless of geographical region. In the second 30-year period, when the planting of Scots pine increased, the volume growth increased under current climate by up to 8%, compared to baseline management, with the greatest increase in the south. When the planting of birch increased, it either increased the volume growth by up to 7% in the south, or decreased it by up to 4% in the north. In the third 30-year period, the increase in the planting of Norway spruce increased volume growth under the current climate by up to 9%, with the greatest increase in the north, opposite to the pattern shown by birch**.**

Under changing climate, the increase in the planting of Norway spruce in the south decreased volume growth the most, compared to the baseline management, that is, by up to 24% in the last 30-year period under the multi-model mean of RCP8.5. At the same time, the increase in the planting of birch either increased it by up to 39% in the south, or decreased it by up to 12% in the north, depending on the multi-model mean of RCP4.5 and RCP8.5. When the planting of Scots pine increased, volume growth increased by up to 7%, compared to baseline management (**Fig. 3**).

Under the individual GCM projections, volume growth varied from 2.4 to 9.8 m^3 ha^{-1} a^{-1} in the south, and from 2.8 to 6.4 m^3 ha^{-1} a^{-1} in the north, from the first to last 30-year period. In general, the range between GCM projections increased in the last 30-year period, and the preference of birch increased volume growth especially in the south (**Fig. 3**, **Appendix Table A1**). Under individual GCM projections, such as CNRM 8.5, volume growth increased more than under the multi-model means of RCP4.5 and RCP8.5, with a preference for Scots pine and birch. It also decreased under CNRM 8.5 less due to preference of Norway spruce than under the multi-model mean of RCP8.5 (**Fig. 3**). Under HadGEM2 8.5, volume growth decreased in the south, even with birch, compared to the multi-model means of RCP4.5 and RCP8.5. Both the preference for Norway spruce and Scots pine decreased volume growth in the south under GFDL 8.5 and HadGEM2 8.5. In the north, volume growth was at its lowest under HadGEM2 8.5, with Norway spruce decreasing volume growth the most (**Fig. 3**).

The climate projection affected volume growth in the long term more than did the increase in the planting of a certain tree species, and especially in northern Finland (**Fig. 3**).

Fig. 3

Fig. 4

3.3 Forest ecosystem carbon stock

Under current climate, with baseline management, the carbon stock (in trees and soil) of forests increased in the south from 79 to 87 Mg ha^{-1}, and in the north from 72 to 88 Mg ha^{-1}, from the first to last 30-year period (**Figs 3 and 5**). The use of certain tree species in forest regeneration had only a marginal effect on the carbon stock of forests in the first 30-year period, regardless of geographical region. The increase in the planting of Norway spruce and birch under current climate increased the carbon stock of forests by up to 12% in the south in the last 30-year period. Correspondingly, the increase in the planting of Scots pine decreased it by up to 4% in the north.

Under changing climate, the increase in the planting of Norway spruce decreased the carbon stock of forests the most, by up to 9%, in the south under the multi-model mean of RCP8.5 in the last 30-year period, compared to baseline management. Also, the increase in the planting of Scots pine decreased it to some degree, whereas the increase in the planting of birch increased it by up to 29% (**Fig. 3**).

Under the individual GCM projections, the carbon stock varied from 48 to 105 Mg ha $^{-1}$ in the south, and from 74 to 120 Mg ha^{-1} in the north, from the first to last 30-year period. In general, the carbon stock was lower in the south than in the north in the last 30-year period. The increase in the planting of birch increased carbon stock especially in the north. The increase in planting of Norway spruce decreased the carbon stock in the south, especially under severe GCMs projections, such as HadGEM2 8.5 and GFDL 8.5 (**Fig. 3, Appendix Table A2**). Under HadGEM2 8.5 and GFDL 8.5, the carbon stock decreased in the south, compared to current climate, regardless of tree species, and the decrease was larger than under the multi-model mean of RCP8.5. In the north, the carbon stocks increased under HadGEM2 8.5 and GFDL 8.5, compared to current climate, but they were lower than under the multi-model mean of RCP8.5 (**Fig. 3**). The climate projection affected the ecosystem carbon stock in the long term more than did the increase in planting of a certain tree species, especially in the north (**Fig. 3**).

Fig. 5

3.4 Timber yield

Under current climate with baseline management, the mean annual timber yield range was, in the south, 4.2–4.3 $m^3 ha^{-1} a^{-1}$ and, in the north, 1.5–1.8 $m^3 ha^{-1} a^{-1}$ for the first and last 30-year period (**Fig. 3**). Using certain tree species in forest regeneration had a marginal effect on timber yield in the first 30-year period, regardless of region. The increase in the planting of Norway spruce and Scots pine, under current climate, increased the timber yield, the most by up to 18%, with the planting of Norway spruce in the north in the last 30-year period. Correspondingly, the increase in the planting of birch decreased it the most in the south, by up to 27%.

Under changing climate, the increase in the planting of Norway spruce decreased timber yield the most in the south, by up to 35%, compared to baseline management, in the last 30-year period, under the multi-model mean of RCP8.5. At the same time, the increase in the planting of Scots pine increased timber yield the most in the south, by up to 27%. However, the increase in the planting of birch increased the timber yield by up to 42% in the south, and decreased it by up to 43% in the north, under the multi-model mean of RCP8.5 (**Fig. 3**).

Under the individual GCM projections, timber yield varied from 0.9 to 6.7 $m^3 ha^{-1} a^{-1}$ in the south, and from 1.5 to 3.9 $m^3 ha^{-1} a^{-1}$ in the north, from the first to the last 30-year period (**Fig. 3, Appendix Table A3**). In general, the severe GCM projections, such as HadGEM2 8.5 and GFDL 8.5, decreased timber yield, compared to the multi-model mean of RCP8.5 in the south, with the increase in planting of birch being an exception (**Fig. 3**). Under HadGEM2 8.5 and GFDL 8.5, timber yield in the north could be increased by increasing planting of Scots pine (**Fig. 3**). The climate projection affected timber yield in the long term more than did the increase in the planting of a certain tree species, especially in the north (**Fig. 3**).

4. Discussion

We employed a well validated forest ecosystem model (SIMA) to study how using certain tree species in forest regeneration affected the tree species proportions, volume growth, timber yield, and carbon stock of boreal upland forests in Finland, under the current climate and recent-generation GCM predictions (i.e., multi-model means and individual GCMs of CMIP5), under representative concentration pathways RCP4.5 and RCP8.5 forcing scenarios, over the period 2010–2099. Under certain most severe climate warming projections from individual GCMs, temperature increased greatly compared to current climate, whereas precipitation either increased or decreased during the potential growing season by 2100. Under the multi-model mean climate projections, both temperature and precipitation increased towards 2100.

The initial site and stand characteristics used in the simulations were based on the NFI10 of Finland, on upland forest land assigned to timber production. Although we used only one permanent sample plot from every NFI cluster, the sample plots used were taken to be a representative sample of Finnish forests, and their number was large enough to produce reliable results at the regional level. Our results are the most applicable for upland forests, which cover 67% of the total forest area in Finland. They are, however, also applicable with reservations to well-drained peatlands with similar fertility (excluding the results for carbon in soil).

We used alternative climate projections in the simulations to evaluate the impacts of their use on tree species proportions, volume growth, timber yield, and carbon stock of boreal forests. This was done because, depending on the climate projection applied, even opposing climate impacts can be predicted, and they can significantly affect the interpretation of results. This can further result in costly over-adaptation or mal-adaption of the projected climate change (Ekström et al. 2016). It should also be noted that the use of multi-model mean changes in projected climate variables can result in physically unrealizable changes in climate variables, especially if applied on a daily scale (Madsen et al. 2017), which was not the case in our study. Also, depending on the selected subset of CGMs, the predicted impacts may be very different (Ahlström et al. 2012; Wilcke et al. 2016).

In our study, the impacts of climate projections on volume growth, carbon stocks, and timber yield varied widely for different tree species and boreal regions. Under some of the most severe GCM projections, such as CNRM-CM5 RCP8.5, HadGEM2-ES RCP8.5, and GFDL-CM3 RCP8.5, the predicted impacts were larger than those based on the multi-model mean of RCP8.5, respectively. The degree of variability in the impacts of tree species preferences in forest regeneration increased, when the severity of the climate change projection increased. For example, the proportion and growth of Norway spruce decreased in line with the severity of climate change, in opposite to birch, even though its planting increased in southern Finland. This was mainly due to the difference in species-specific responses to the temperature sum. In addition, soil moisture availability also may have limited growth, especially in Norway spruce in the south.

On the other hand, longer and warmer growing seasons may have also increased the supply of nutrients for growth, due to an enhanced decomposition of litter and soil organic matter. In addition, the elevation of atmospheric CO_2 increased growth, which has also been found in previous studies (e.g., Peltola et al. 2002; Ellsworth et al. 2012; Kellomäki et al. 2018). These factors could not, however, compensate for the effects of the most severe climate warming, which made the growing conditions suboptimal, especially for Norway spruce, and partially for Scots pine, in the south. As a result, increasing planting of a certain tree species on medium fertile sites (52% of all sample plots) affected the development of forest structure in the long run more than climate projection did.

The predicted decrease in growth (and increased mortality) in Norway spruce, especially under severe climate change projections of CMIP5, could be explained, at least partially, by currently near optimal temperature (temperature sum) conditions for its growth (Kellomäki et al. 2008, 2018). By comparison, in northern Finland, climate change may make the thermal growing conditions more optimal for growth in general, regardless of tree species. Some previous experimental studies have also shown that the growing conditions may become suboptimal, especially for Norway spruce, in the most southern upland forest sites in Finland, under the warming climate associated with drought (Mäkinen et al. 2000, 2001, 2002; Jyske et al. 2010). On the other hand, growth may also reduce in Scots pine at high northern latitudes due to drought (Henttonen et al. 2015). Especially severe climate warming, and an associated increase in drought, may make the future growing conditions suboptimal for some tree species, but more optimal for others (e.g., Kellomäki et al. 2001, 2008; Allen et al. 2010; Lindner et al. 2010; Granda et al. 2013; Taeger et al. 2013).

With increased planting of Norway spruce on medium fertile upland forest sites, volume growth, timber yield, and carbon stock decreased in southern Finland, and the most under severe climate change. This was oppose to increasing the planting of silver birch, regardless of climate change severity. This was also the case when increasing planting of Scots pine and use of baseline management under mild climate change. In northern Finland, volume growth, timber yield, and carbon stock increased compared to the current climate, regardless of the severity of the climate change. There, the climate projection also affected the results more than did the use of different tree species in forest regeneration. The impacts were the highest under GCM, like CNRM-CM5 RCP8.5, and with the multi-model mean of RCP8.5. Also increased planting of silver birch decreased timber yield, compared to baseline management, regardless of climate projection, as did increased planting of Norway spruce under the most severe climate projections.

The severity of the climate change, and the initial forest structure and intensity of forest management, affect all the predicted changes in tree species proportions, volume growth, timber yield, and carbon stock of forests in different regions. In northern Finland, older forests dominated at the beginning of the simulation (Finnish Forest Research Institute 2014). Clearly, a larger proportion of forest area there is under forest conservation, compared to other parts of Finland. In addition, forests in northern Finland were dominated by Scots pine, and in southern Finland by Norway spruce. Especially under severe climate warming, the expected increase in the frequency and duration of droughts in spring and summer (e.g., Ruosteenoja et al. 2018) may make growing conditions suboptimal, especially for Norway spruce, but partially also for Scots pine, and more optimal for broadleaves across boreal and temperate regions (Lindner et al. 2010, 2014; Kolström et al. 2011; Schäfer et al. 2017), which needs to be considered when adapting management strategies to climate change.

We did not consider either a possible increase in various abiotic and biotic risks of forests under climate change in our simulations, which may, at least partially, counteract the expected increase in forest productivity (see, e.g., Reyer et al. 2017; Seidl et al. 2017). Especially, increasing the cultivation of Norway spruce may increase the risk of various biotic, e.g., *Heterobasidion* spp. and bark beetles, such as *Ips typographus*, and abiotic damage, e.g., from windstorms and drought, respectively (see, e.g., Peltola et al. 2010; Subramanian et al. 2016; Thom and Seidl 2016; Honkaniemi et al. 2017; Ruosteenoja et al. 2018). On the other hand, also Scots pine and birches (in leaf) are vulnerable to wind-induced damage (e.g. Peltola et al. 2010), which are expected to increase due to decrease in duration of frozen soil under a warming climate, and the most in southern and central boreal conditions. Additionally, Scots pine and birches are in general more vulnerable to snow-induced damage than Norway spruce (Peltola et al. 1999; 2010), which risks are also expected to increase in middle and northern boreal conditions (Lehtonen et al. 2016a).

The increasing abiotic and biotic risks of forests and forestry need to be considered carefully when adapting forest management practices to accommodate climate change, in order to mitigate its harmful effects. For example, by favoring mixed-species forestry, instead of only pure conifers based forestry, we may be able to maintain higher forest productivity (see Mielikäinen 1980, 1985; Pretzsch and Schütze 2016). This may also make possible to modify in a flexible way the management strategies to the realized climate change and associated risks to forests and forestry. Thoughtful adaptation to climate change is crucial because there is a pressure to greatly increase volume growth in Finnish forests like elsewhere in Europe to both fulfill the increasing demand for wood by the expanding forest-based bioeconomy, and climate change mitigation targets (The Ministry of Employment and the Economy 2014; COM/2014/0015 2014).

5. Conclusions

Our study demonstrates that the magnitude of climate change impacts depends largely on the tree species used in forest regeneration, geographical region, and the severity of the climate projection. The severity of the climate change largely affects the degree of variability in the impacts of tree species preferences on volume growth, timber yield, and carbon stock of forests in different regions. Increasing the planting of a certain tree species affects the development of forest structure more than the climate projections, in the long term. Based on our findings, different adaptive measures may be needed, depending on the region, the severity of the climate change, and the targets set for forest management. These may also help, at least partially, to counteract the expected decrease in forest productivity in southern boreal conditions under severe climate change. In future studies, it should be considered also the potential risks to forests by increasing abiotic and biotic forest damages under climate change. A representative set of climate projections should be used simultaneously to examine the uncertainties related to the projected climate change and its impacts on forests and forestry.

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Figure captions

Fig. 1. Outlines of the SIMA model used in simulations.

Fig. 2. Proportion (% stem volume) of Scots pine, Norway spruce and birch under current climate (CU), and multi-model means and a subset of GCMs of CMIP5 under RCP4.5 and RCP8.5 forcing scenarios, with different management regimes (pref. SP: Scots pine, pref. NS: Norway spruce, pref. B: birch preference in forest regeneration) in southern and northern Finland in the last 30-year period of 2070–2099.

Fig. 3. Left: Stem volume growth (m^3 ha^{-1} a^{-1}), timber yield (m^3 ha^{-1} a^{-1}), and carbon stock (Mg ha^{-1}) of forests under current climate (CU), and multi-model means and a subset of GCMs of CMIP5 under RCP4.5 and RCP8.5 forcing scenarios, with different management regimes (pref. SP: Scots pine, pref. NS: Norway spruce, pref. B: birch preference in forest regeneration) in southern and northern Finland. Middle: Effects of climate change (%) compared to current climate. Right: Effects of management (%) compared to baseline management.

Fig. 4. Mean annual volume growth (m^3 ha^{-1} a^{-1}) of Finnish forests with a baseline management regime under current climate (CU), and multi-model means and a subset of GCMs of CMIP5 under RCP4.5 and RCP8.5 forcing scenarios, together with effects of tree species preferences in forest regeneration (pref. Scots pine, pref. Norway spruce and pref. birch) on mean annual volume growth (growth change, %), compared to baseline management in the last 30-year period of 2070–2099.

Fig. 5. Mean annual carbon stock (Mg ha^{-1}) of Finnish forests with a baseline management regime under current climate (CU), and multi-model means and a subset of GCMs of CMIP5 under RCP4.5 and RCP8.5 forcing scenarios, together with effects of tree species preferences in forest regeneration (pref. Scots pine, pref. Norway spruce and pref. birch) on the mean annual carbon stock (change of carbon stock, %), compared to baseline management in the last 30-year period of 2070–2099.

Tables

Table 1. Mean changes in temperature (ΔT, °C) and precipitation (ΔP, %) under different CMIP5 projections (i.e., multi-model means and individual GCMs) during potential growing seasons (April–September) in the period 2070–2099 in southern (old Forest Centre Units 1–6) and northern (old Forest Centre units 10–13) Finland, in comparison to current climate (1981–2010, with a mean atmospheric CO_2 concentration of 360 ppm), and predicted mean atmospheric CO_2 concentrations (ppm) under the RCP4.5 and RCP8.5 forcing scenarios for the period 2070–2099, respectively (country of origin and other information for individual GCMs available in Ruosteenoja et al. 2016).

Climate	**Short name**	**ΔT (°C)**		**ΔP (%)**		**CO_2 (ppm)**
		South	**North**	**South**	**North**	
HadGEM2-ES RCP4.5	HadGEM2 4.5	3.5	3.7	2	8	536
HadGEM2-ES RCP8.5	HadGEM2 8.5	6.1	6.1	-9	7	807
MPI-ESM-MR RCP4.5	MPI 4.5	1.6	1.8	1	4	536
MPI-ESM-MR-RCP8.5	MPI 8.5	2.8	3.1	6	4	807
CanESM2 RCP4.5	CanESM2 4.5	3.3	3.6	12	13	536
CanESM2 RCP8.5	CanESM2 8.5	5.9	6.3	7	13	807
MIROC5 RCP4.5	MIROC5 4.5	3.2	3.3	9	11	536
MIROC5 RCP8.5	MIROC5 8.5	5.6	6	13	15	807
CNRM-CM5 RCP8.5	CNRM 8.5	3.7	3.9	24	19	807
GFDL–CM3 RCP8.5	GFDL 8.5	6.3	7	14	26	807
Mean RCP4.5	Mean RCP4.5	2.6	2.9	7	10	536
Mean RCP8.5	Mean RCP8.5	4.6	4.9	9	14	807

Table 2. Simulation layout with initial stand and site conditions, alternative climate projections and management activities.

Simulation layout	**Description**
Initial stand and site conditions	The initial stand and site characteristics were based on the NFI (NFI10) of Finland. Forest inventory data consisted of one randomly selected sample plot from every permanent cluster of sample plots on upland forest land assigned to timber production. The average distance between the clusters of sample plots is 6×6 km throughout Finland, excluding northernmost Finland (Forest Centre unit 13), where it is 10 × 10 km (Korhonen 2016). In the NFI, trees belonging to the sample plot were determined with an angle gauge (relascope). Each sample plot had on average of nine trees. Variables available for all sample trees included tree species and diameter at breast height (dbh, cm).
Initial amount of soil organic matter (and carbon) and nitrogen available for growth	The initial amounts of soil organic matter (and carbon) and nitrogen available for growth were defined based on the site fertility type and regional temperature sum of the current climate. Additionally, a nitrogen deposition of 10 kg year^{-1} was used, regardless of the site.
Climate data	Current climate data (1981–2010), multi-model mean values for RCP4.5 and RCP8.5 forcing scenarios, and four individual GCM projections under RCP4.5 and six under RCP8.5 forcing scenarios (2010–2099).
Forest regeneration and tending of seedling stand	In a baseline management, forest regeneration was performed by planting the same tree species that was dominant before the final cut. In alternative management regimes, either Scots pine, Norway spruce or silver birch was planted on medium fertile (MT) sites. In planting, we used 2,000 seedlings ha^{-1} for Norway spruce and Scots pine, and 1,600 seedlings ha^{-1} for silver birch, with an initial diameter of 2.5 cm. In addition, seedlings were also expected to regenerate naturally at all sites.
Tending of seedling stand	Tending of the seedling stand was carried out, if needed, before the first commercial thinning by removing mostly smaller or suppressed trees.
Thinnings and final felling	The region, site and tree species-specific Finnish management recommendations were used as a basis for the timing and intensity of thinnings, and timing of final felling, respectively. Based on these, when the basal area threshold for thinning was reached, at a given dominant height, the thinning could be done by reducing the basal area to the recommended threshold value after thinning. Final felling was performed based on the basal area weighted diameter at breast height (with a range 22–30 cm depending on region, site and tree species). However, on average, a 13-year delay in thinnings and final fellings was used, compared to the management recommendations, because these are often delayed in practice.
Harvesting intensity	In thinning and final felling, only timber (sawlogs and pulpwood with minimum top diameters of 15 cm and 6 cm, respectively) was harvested, and logging residues were left at the site.
Other information	Parts of the forest plots from central (10%) to northern (30%) Finland were left outside management, unlike in southern Finland.

Appendix

Table A1. Mean annual volume growth (m^3 ha^{-1} a^{-1}) under each climate change projection and management regime.

	Baseline		**Pref. pine**		**Pref. spruce**		**Pref. birch**	
	South	**North**	South	North	South	North	South	North
2010–2039								
CU	5.8	2.8	5.9	2.8	5.8	2.8	5.9	2.8
HadGEM2 4.5	6.3	3.7	6.3	3.7	6.1	3.6	6.4	3.7
HadGEM2 8.5	6.4	3.9	6.4	3.9	6.1	3.8	6.6	3.9
MPI 4.5	6.4	3.5	6.4	3.5	6.2	3.4	6.5	3.4
MPI 8.5	6.5	3.5	6.5	3.5	6.3	3.5	6.6	3.5
CanESM2 4.5	6.4	3.9	6.4	3.9	6.2	3.8	6.6	3.8
CanESM2 8.5	6.5	4.1	6.5	4.1	6.2	3.9	6.7	4.0
MIROC5 4.5	6.4	4.0	6.4	4.0	6.1	3.8	6.6	3.9
MIROC5 8.5	6.4	4.1	6.4	4.1	6.1	4.0	6.6	4.1
CNRM 8.5	6.6	3.8	6.6	3.8	6.4	3.7	6.8	3.7
GFDL 8.5	6.5	4.3	6.5	4.3	6.2	4.1	6.8	4.3
Mean RCP4.5	6.5	3.7	6.5	3.7	6.2	3.6	6.6	3.6
Mean RCP8.5	6.6	3.8	6.6	3.8	6.3	3.7	6.7	3.8
2040–2069								
CU	5.6	2.9	6.0	2.9	5.7	3.0	6.0	2.8
HadGEM2 4.5	6.2	5.1	6.6	5.1	5.3	4.7	7.6	4.8
HadGEM2 8.5	5.5	5.4	6.0	5.5	4.4	4.8	7.4	5.3
MPI 4.5	7.0	4.5	7.2	4.4	6.4	4.3	7.4	4.2
MPI 8.5	7.0	5.0	7.4	5.0	6.4	4.8	7.8	4.7
CanESM2 4.5	6.6	5.3	7.0	5.3	5.7	4.9	8.0	5.1
CanESM2 8.5	6.1	5.7	6.5	5.7	4.9	5.1	8.1	5.5
MIROC5 4.5	6.6	5.3	7.0	5.3	5.6	4.9	8.0	5.0
MIROC5 8.5	6.2	5.7	6.6	5.8	5.0	5.1	8.1	5.5
CNRM 8.5	7.4	5.5	7.8	5.5	6.6	5.2	8.5	5.2
GFDL 8.5	6.3	5.8	6.5	6.0	5.1	5.2	8.6	5.9
Mean RCP4.5	6.9	4.9	7.3	4.9	6.2	4.7	7.8	4.6
Mean RCP8.5	6.8	5.5	7.3	5.6	5.9	5.2	8.2	5.3
2070–2099								
CU	7.0	3.3	6.9	3.2	7.2	3.6	6.4	3.0
HadGEM2 4.5	6.6	5.6	6.8	5.5	5.5	5.5	8.3	4.9
HadGEM2 8.5	3.2	4.8	3.0	4.9	2.4	3.9	5.4	4.8
MPI 4.5	8.0	5.0	8.0	4.9	7.9	5.2	7.7	4.4
MPI 8.5	7.9	6.0	8.2	6.0	7.3	6.1	8.5	5.3
CanESM2 4.5	7.4	5.7	7.5	5.6	6.5	5.7	8.7	5.0
CanESM2 8.5	4.6	5.2	4.4	5.4	3.4	4.4	7.5	5.2
MIROC5 4.5	7.4	5.7	7.5	5.6	6.3	5.7	8.9	5.0
MIROC5 8.5	5.6	5.6	5.4	5.7	4.2	5.0	8.9	5.5
CNRM 8.5	7.7	6.4	8.2	6.4	6.6	6.4	9.5	5.8
GFDL 8.5	6.2	5.6	5.3	5.8	4.5	4.8	9.8	5.9
Mean RCP4.5	7.7	5.5	7.8	5.4	7.3	5.6	8.3	4.8
Mean RCP8.5	6.4	6.1	6.8	6.2	4.8	5.9	8.8	5.6

Table A2. Total ecosystem carbon stock (Mg ha^{-1}) under each climate projection and management regime.

	Baseline		**Pref. pine**			**Pref. spruce**		**Pref. birch**	
	South	North	South	North	South	South	North	South	North
2010–2039									
CU	79	72	79	72		79	72	79	72
HadGEM2 4.5	79	74	79	74		79	74	80	74
HadGEM2 8.5	79	75	79	75		79	75	80	75
MPI 4.5	80	74	80	74		79	74	80	74
MPI 8.5	80	74	80	74		79	74	80	74
CanESM2 4.5	80	75	79	75		79	75	80	75
CanESM2 8.5	79	75	79	75		79	75	80	75
MIROC5 4.5	79	75	79	75		79	75	80	75
MIROC5 8.5	79	75	79	75		78	75	80	75
CNRM 8.5	80	74	80	74		79	74	80	74
GFDL 8.5	79	75	79	75		78	75	80	76
Mean RCP4.5	80	74	80	74		79	74	80	74
Mean RCP8.5	80	74	80	74		79	74	80	74
2040–2069									
CU	74	77	75	76		76	79	81	78
HadGEM2 4.5	76	90	75	87		71	89	86	92
HadGEM2 8.5	72	91	72	89		67	90	85	95
MPI 4.5	80	88	78	85		77	88	87	88
MPI 8.5	80	89	78	87		77	89	88	90
CanESM2 4.5	77	92	75	88		72	91	88	94
CanESM2 8.5	74	93	73	90		69	92	87	97
MIROC5 4.5	76	92	75	89		72	91	87	94
MIROC5 8.5	74	93	73	90		68	92	87	97
CNRM 8.5	79	91	78	88		76	91	89	93
GFDL 8.5	73	93	72	90		66	91	87	98
Mean RCP4.5	78	89	77	86		75	89	87	90
Mean RCP8.5	78	92	76	89		73	91	88	94
2070–2099									
CU	87	88	85	84		92	94	98	91
HadGEM2 4.5	79	109	77	102		75	113	100	116
HadGEM2 8.5	57	101	56	95		48	101	79	113
MPI 4.5	93	107	87	100		94	112	105	112
MPI 8.5	90	112	85	105		88	116	106	119
CanESM2 4.5	84	111	80	104		80	115	103	118
CanESM2 8.5	63	104	63	98		55	105	88	116
MIROC5 4.5	83	109	79	103		78	114	102	117
MIROC5 8.5	67	106	66	99		58	108	91	116
CNRM 8.5	85	112	82	105		82	117	104	120
GFDL 8.5	68	104	64	99		57	105	92	116
Mean RCP4.5	89	109	84	102		88	113	105	115
Mean RCP8.5	77	111	75	105		70	115	99	120

Table A3. Mean annual timber yield (m^3 ha^{-1} a^{-1}) under each climate projection and management regime.

	Baseline		**Pref. pine**		**Pref. spruce**		**Pref. birch**	
	South	North	South	North	South	North	South	North
2010–2039								
CU	4.3	1.8	4.3	1.8	4.3	1.8	4.3	1.8
HadGEM2 4.5	4.6	2.2	4.5	2.2	4.5	2.3	4.6	2.2
HadGEM2 8.5	4.7	2.3	4.6	2.3	4.6	2.3	4.6	2.3
MPI 4.5	4.7	2.1	4.6	2.1	4.6	2.1	4.7	2.2
MPI 8.5	4.7	2.2	4.7	2.1	4.7	2.2	4.7	2.2
CanESM2 4.5	4.6	2.3	4.6	2.3	4.6	2.3	4.7	2.3
CanESM2 8.5	4.7	2.4	4.6	2.4	4.6	2.4	4.7	2.4
MIROC5 4.5	4.6	2.4	4.6	2.4	4.5	2.3	4.6	2.4
MIROC5 8.5	4.6	2.4	4.6	2.4	4.5	2.4	4.6	2.4
CNRM 8.5	4.8	2.3	4.8	2.2	4.7	2.2	4.8	2.3
GFDL 8.5	4.7	2.5	4.7	2.5	4.6	2.5	4.6	2.5
Mean RCP4.5	4.7	2.3	4.7	2.2	4.7	2.2	4.7	2.2
Mean RCP8.5	4.7	2.3	4.7	2.3	4.7	2.3	4.7	2.3
2040–2069								
CU	4.4	1.8	4.6	1.9	4.4	1.8	4.2	1.8
HadGEM2 4.5	4.3	2.5	4.5	2.5	3.8	2.2	4.5	2.3
HadGEM2 8.5	3.8	2.6	4.1	2.7	3.3	2.3	4.4	2.5
MPI 4.5	4.8	2.4	5.1	2.3	4.5	2.2	4.6	2.1
MPI 8.5	4.8	2.5	5.1	2.5	4.5	2.3	4.7	2.3
CanESM2 4.5	4.5	2.6	4.8	2.7	4.1	2.3	4.8	2.3
CanESM2 8.5	4.2	2.8	4.5	2.8	3.6	2.3	4.8	2.4
MIROC5 4.5	4.5	2.6	4.8	2.7	4.0	2.3	4.8	2.3
MIROC5 8.5	4.2	2.8	4.4	2.8	3.6	2.3	4.7	2.4
CNRM 8.5	4.9	2.7	5.3	2.7	4.6	2.5	5.0	2.4
GFDL 8.5	4.1	2.8	4.2	3.0	3.5	2.3	5.0	2.7
Mean RCP4.5	4.8	2.5	5.0	2.5	4.4	2.3	4.7	2.3
Mean RCP8.5	4.7	2.7	5.0	2.7	4.1	2.4	4.9	2.4
2070–2099								
CU	4.2	1.5	4.7	1.5	4.5	1.8	3.1	1.1
HadGEM2 4.5	4.0	3.3	4.9	3.4	2.8	3.2	5.2	1.8
HadGEM2 8.5	1.5	2.9	1.8	3.2	0.9	2.2	3.3	1.9
MPI 4.5	5.4	2.8	6.0	2.8	5.1	3.0	4.1	1.5
MPI 8.5	5.2	3.5	6.1	3.5	4.5	3.6	4.7	1.8
CanESM2 4.5	4.6	3.4	5.4	3.5	3.5	3.4	5.5	1.8
CanESM2 8.5	2.6	3.2	3.0	3.5	1.5	2.5	4.9	2.2
MIROC5 4.5	4.6	3.4	5.3	3.5	3.4	3.4	5.7	1.8
MIROC5 8.5	3.3	3.5	3.7	3.7	2.0	3.0	5.9	2.2
CNRM 8.5	5.2	3.9	6.2	4.0	4.0	3.9	5.9	2.2
GFDL 8.5	3.6	3.5	3.5	3.7	2.4	2.8	6.7	2.8
Mean RCP4.5	5.1	3.2	5.8	3.2	4.5	3.2	4.9	1.7
Mean RCP8.5	4.0	3.7	5.0	3.9	2.6	3.6	5.6	2.1

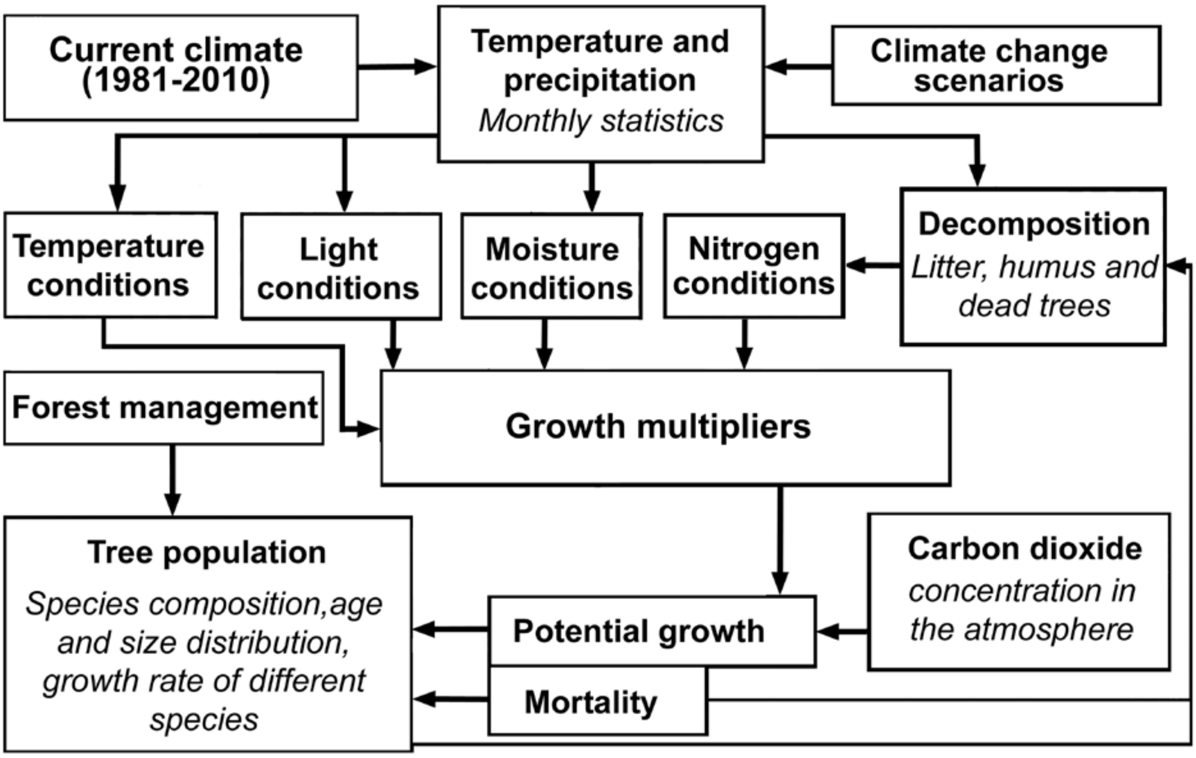

Fig. 1.

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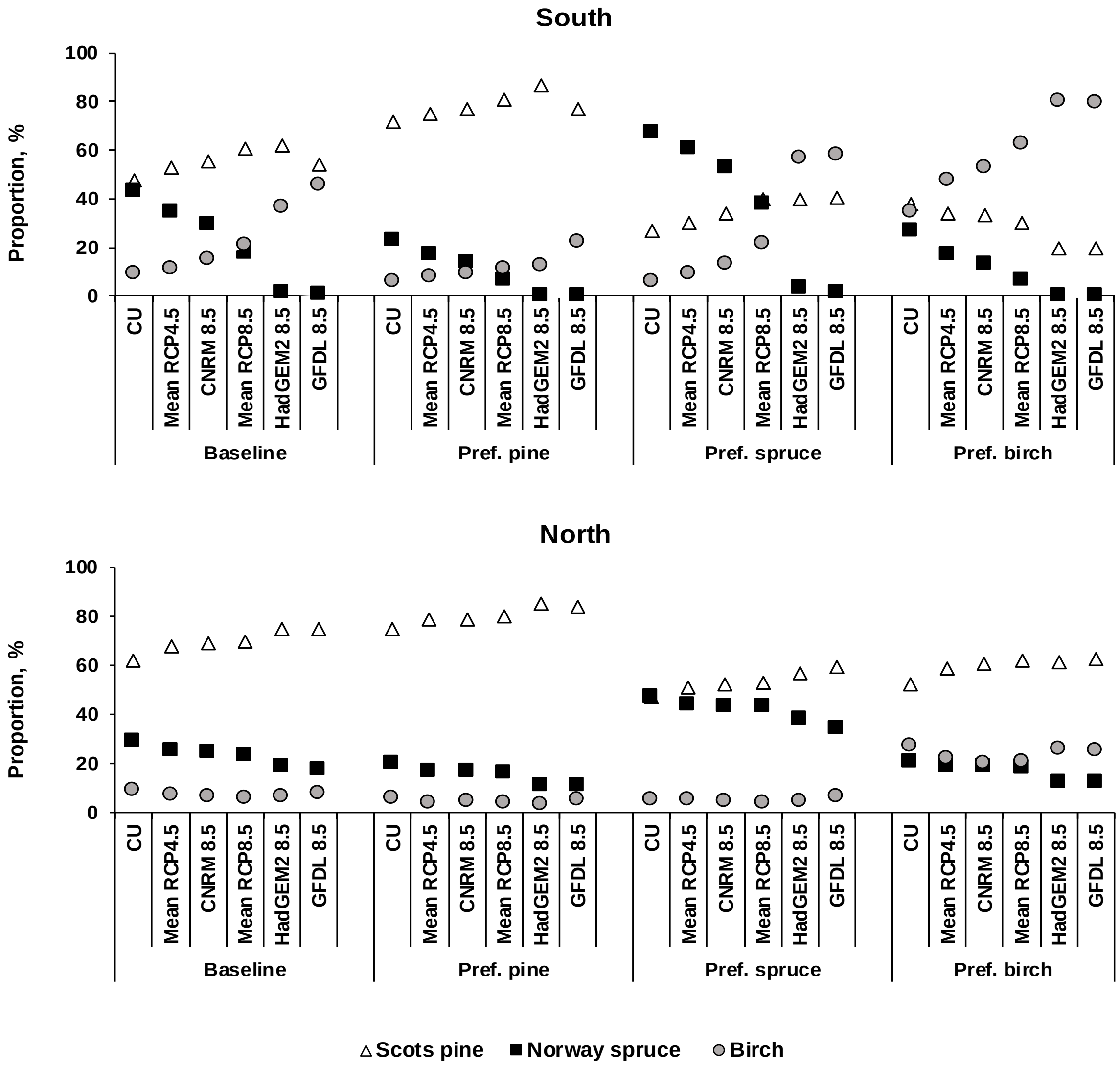

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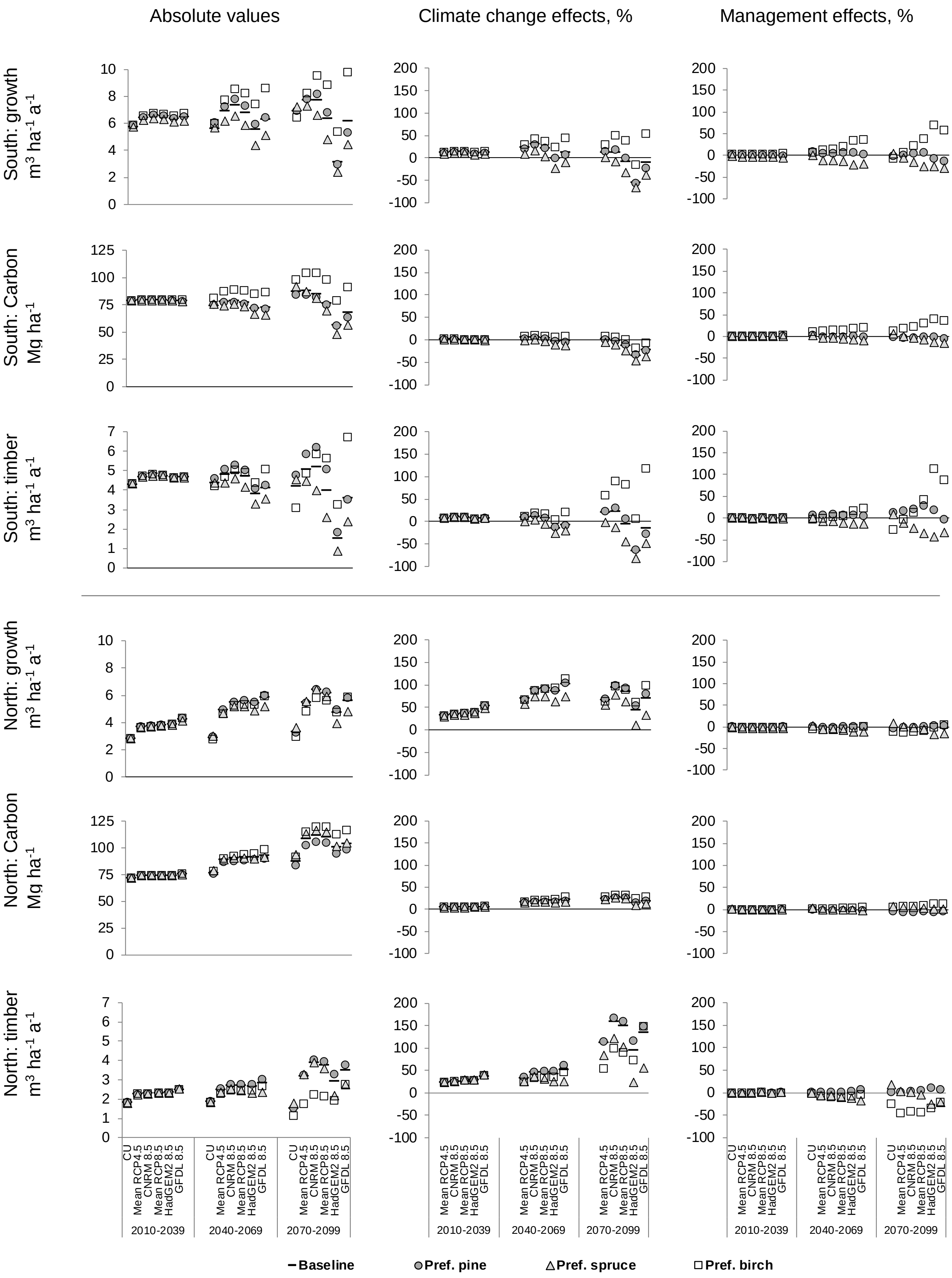

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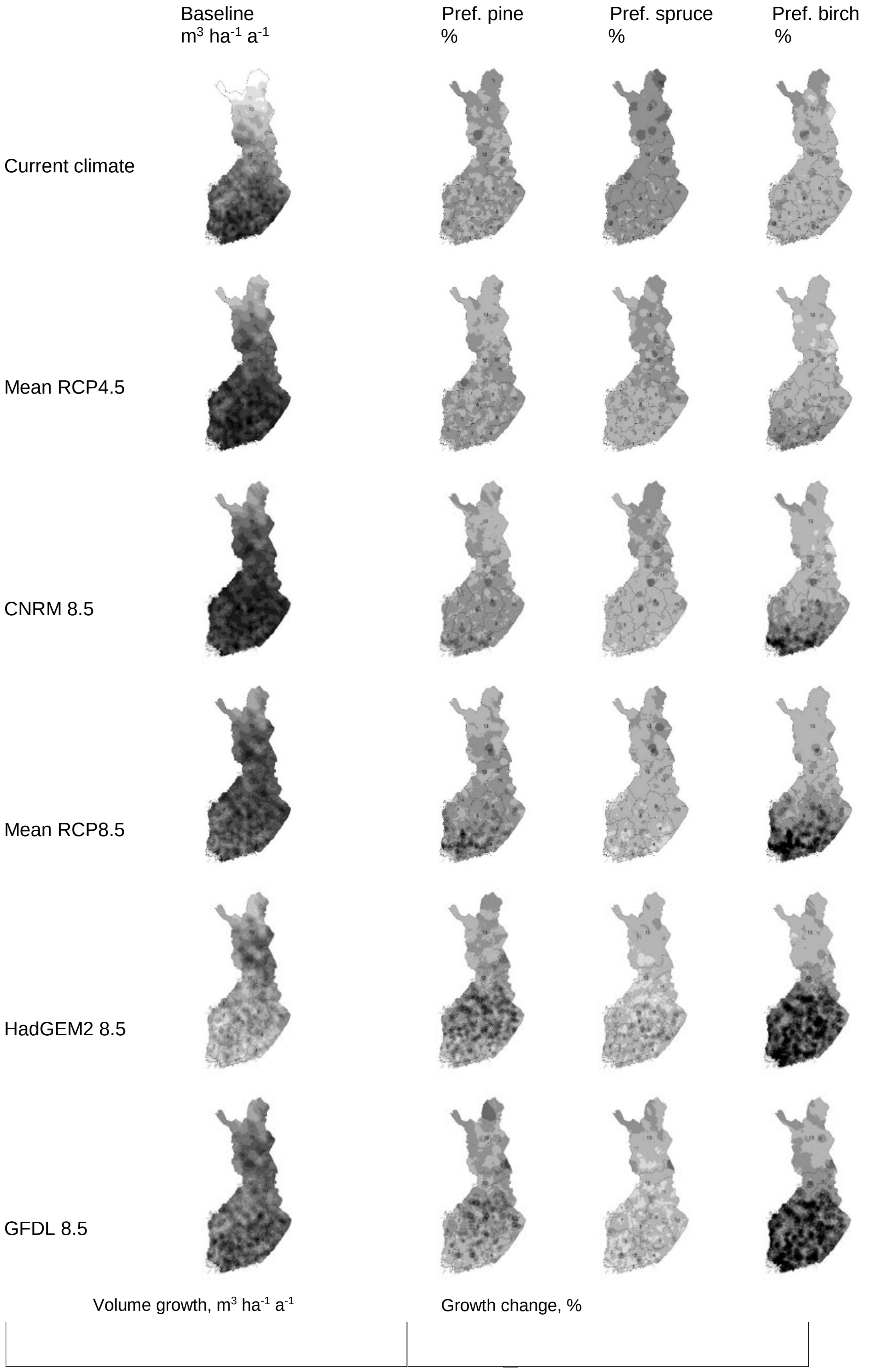

Fig. 4.

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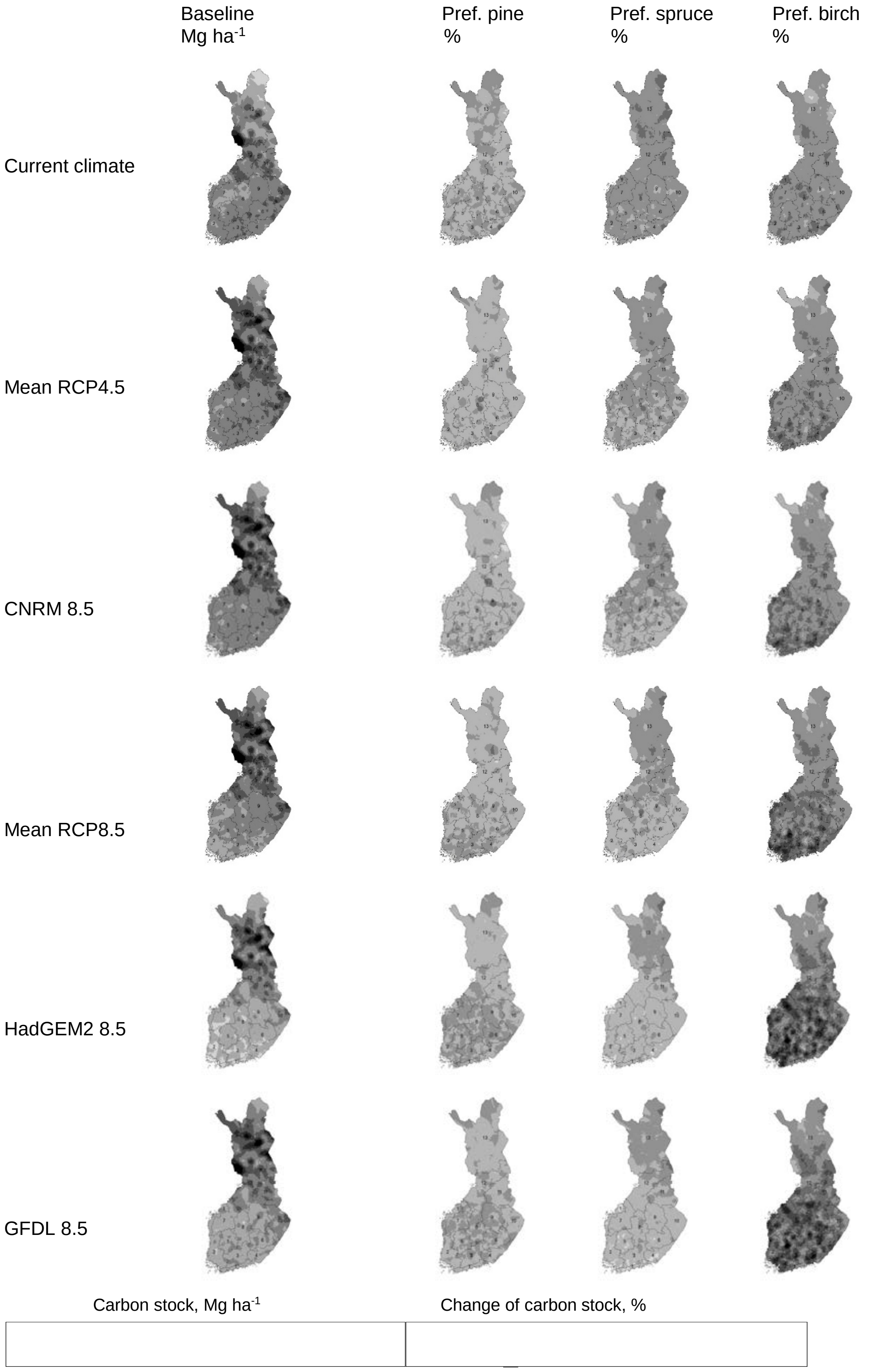

Fig. 5.

Individual maps and labels made by ArcMap, imported as JPG format.