2017

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Canadian Science Publishing

info:eu-repo/semantics/article



http://dx.doi.org/10.1139/cjfr-2016-0153

# Effects of forest conservation and management on volume growth, harvested amount of timber, carbon stock and amount of deadwood in Finnish boreal forests under changing climate

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**Abstract**

We employed a forest ecosystem model (SIMA) to study how the changes in forest conservation area and management affect the volume growth, harvested amount of timber, carbon stock and amount of dead wood in Finnish boreal upland forests under current and changing climate (RCP4.5 and RCP8.5) over 2010–2099. Simulations were carried out on national forest inventory plots using three different forest conservation scenarios (baseline, 10% and 20% increase of conservation area) and three thinning regimes (baseline and maintenance of ±20% stocking in thinning compared to recommendations). An increase of forest conservation area increased the volume growth, carbon stock and quantity of dead wood in forests, as did the maintenance of 20% higher stocking in thinning. Maintenance of 20% lower stocking in thinning increased in general the amount of harvested timber, but it could not compensate for the decrease of harvested timber due to increase of conservation area. Climate warming greatly increased all the studied variables in northern Finland, but decreased them in southern Finland, and the most under the strongest climate warming scenario, RCP8.5. Climate warming increased also the quantity of dead wood throughout Finland. To conclude, we found clear trade-offs for production of different ecosystem services.

**Keywords**: Carbon sequestration, wood production, thinning regime, climate change scenarios, forest ecosystem model.

## 1. Introduction

The demand for multiple-use of forests has increased the interest in the conservation planning and management considering the multifunctional role of forests (Cademus et al. 2014). In addition to restoring forest biodiversity and producing timber, forests play an important role in sequestering and storing atmospheric carbon dioxide ($CO_2$). In general, carbon sequestration is highest in young and middle-aged stands (Liski et al. 2001; Hyvönen et al. 2007). The mean annual carbon sequestration and stock and harvested amount of timber per unit land area may also be increased over a rotation by maintaining stocking higher than that currently recommended, resulting in lower harvesting frequency (Garcia-Gonzalo et al. 2007; Pyörälä et al. 2014). On the other hand, in this way dead wood formation may increase, as both growth and mortality will increase with stand density (Mazziotta et al. 2013). The use of longer rotation may also increase the mean annual carbon stocks and harvested amount of timber over a rotation (Liski et al. 2001; Pyörälä et al. 2014). However, at the regional level, the harvested amount of timber may decrease at least in the short term, the opposite to the forest ecosystem carbon stock, if lower harvesting frequency (i.e. a delay in thinning and final cut) is applied. In Finland, the volume of growing stock along with associated carbon stock has been increasing in past few decades due to lower amount of cuttings compared to volume growth of forests. The latter one has also been increased due to enhanced forest management, e.g. use of improved forest regeneration methods, frequent thinnings, forest fertilization and drainage of forests. For example, in 2013 annual cuttings (timber and energy wood) were 63 % of the total annual volume growth of forests, 104 million $m^3$ (Finnish Statistical Year Book of Forestry 2014).

The mean volume of decayed and other dead trees is in managed Finnish forests usually very low (e.g. in south and north on average < 4 and < 8 $m^3$ $ha^{-1}$), compared to the natural forests, where it is usually > 40 $m^3$ $ha^{-1}$ (Siitonen et al. 2000; Finnish Statistical Year Book of Forestry 2014). Dead wood is important from a biodiversity point of view because many threatened species in boreal forests require 20–40 $m^3$ $ha^{-1}$ of deadwood (Müller and Bütler 2010; Junninen and Komonen 2011). In addition to coarse woody debris, branches and stumps and coarse roots are also important for wood-inhabiting species (Norden et al. 2004; Selonen et al. 2005; Küffer et al. 2008). Currently 8.4% of Finnish productive forest land represents protected forests and areas under restricted forestry use and most of it is situated in northern Finland (Finnish Statistical Year Book of Forestry 2014). On the other hand, many forest owners have also recently shown increasing interest to emphasize biodiversity and recreation values in forest management, rather than economic profitability of forest biomass production (Valkeapää and Karppinen 2013).

Along with the projected climate change, the mean annual temperature is expected to increase in Northern Europe by 3–6 C° and mean annual precipitation by 11–18% until 2100, depending on the scenario used for the concentration of greenhouse gases (Taylor et al. 2012; IPCC 2013). The gradually warming climate is expected to increase carbon sequestration, volume growth and harvested amount of timber of boreal forests in Nordic countries (Kellomäki et al. 2008; Poudel et al. 2011, 2012). This is due to longer growing seasons and increasing decomposition of soil organic matter that increases the supply of available nitrogen for growth. However, in the long run the growth and volume of growing stock of Norway spruce (*Picea abies* (L.) Karst.) with shallow rooting may be reduced especially in southern Finland on sites with reduced soil water availability (Kellomäki et al. 2001, 2008; Mäkinen et al., 2001; Ge et al., 2010, 2013a, b). In the short term, also growth of Norway spruce may increase under the warming climate, similar to that of Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth), if water and nitrogen availability are not limiting growth (Torssonen et al. 2015).

At the regional level, the development of forest resources and the production of ecosystem services are affected both by the prevailing environmental conditions (e.g. climate, site), current forest structure (age and tree species), management strategies applied and the degree of climate change (Garcia-Gonzalo et al. 2007; Kellomäki et al. 2008; Hynynen et al. 2015). Their interactive effects may be studied by applying forest ecosystem model simulations together with up-to-date information on current forest resources and alternative climate change scenarios (Kärkkäinen et al. 2008; Kellomäki et al. 2008; Matala et al. 2009; Hynynen et al. 2015). This would not be possible by employing empirical growth models alone, by assuming no change in climate and environment over time. Better understanding of possible trade-offs between different ecosystem services (e.g. forest carbon sequestration and timber production) and how they are affected by alternative forest management and utilization policies (e.g. increase of conservation area and/or management intensity) and changing environmental conditions (e.g. climate, site) are urgently needed for sustainable management and utilization of forest resources (Seidl et al. 2007; Kindermann et al. 2013; Hynynen et all. 2015; Triviño et al. 2015; Bottalico et al. 2016). Alternative projections of climate change should also be considered in such analyses to consider uncertainties related to the projected climate change (Garcia-Gonzalo et al. 2007; Seidl and Lexer 2013). There may be also large trade-offs for production of different ecosystem services like carbon sequestration and stocks in the forest and the harvested amount of timber (Seely et al. 2002; Matala et al. 2009; Hynynen et al. 2015; Triviño et al. 2015).

In this study, we employed a forest ecosystem model (SIMA) to evaluate for the first time how the changes in forest conservation area and management affect the volume growth, harvested amount of timber, carbon stock (in trees and soil) and amount of dead wood (used here as an indicator of biodiversity) in Finnish boreal upland forests under the current climate and changing climate (RCP4.5 and RCP8.5 scenarios) over 2010–2099. The simulations were carried out on $10^{th}$ national forest inventory plots using three alternative forest conservation scenarios (baseline, and 10% and 20% increase of conservation area compared to the baseline) and three alternative thinning regimes (baseline and maintenance of ±20% stocking compared to the baseline, i.e. current Finnish management recommendations). In previous impact studies with the SIMA model from stand to regional level in Finland (Kellomäki et al. 2008; Torssonen et al. 2015), the effects of forest conservation on the volume growth, harvested amount of timber, carbon stock and amount of dead wood were not studied, nor the effects of the newest IPCC (2013) representative concentration pathway climate change scenarios.

## 2. Material and Methods

### 2.1 Outlines for the forest ecosystem model (SIMA)

We used a forest ecosystem model SIMA (Kellomäki et al. 2005, 2008) to simulate the regeneration, growth and mortality of boreal upland forests throughout Finland as affected by temperature sum, soil water and nitrogen availability, within-stand light and atmospheric $CO_2$ concentration, and competition of trees. In the model, the species-specific response to the temperature sum is modeled based on a downwards-opening symmetric parabola (Kellomäki et al. 2008; Torssonen et al. 2015). The maximum ($TS_{max}$, 2060, 2500, 4330 d.d.) and optimum temperature sum for growth ($TS_{opt}$, 1215, 1445, 2360 d.d.) are smallest in Norway spruce, followed by Scots pine and birch. The effects of temperature increase on growth are calculated by considering the changes of monthly temperature sums compared to the current climate from April to September (the potential growing season). This is carried out to meet the currently prevailing light conditions, following the previous study of Torssonen et al. (2015).

In the SIMA model, the soil texture together with field capacity and wilting point define the soil moisture available for growth as a function of precipitation and evaporation. Under climate warming, the reduction of soil moisture has a more negative effect on growth than the increase of temperature sum (Torssonen et al. 2015). Site fertility type also indicates the initial amount of soil organic matter and nitrogen available for growth, and thus also affects the growth and the amount of carbon in forest ecosystem (in soil and trees). The regional temperature sum affects the initial values for soil organic matter (Kellomäki et al. 2008). Input of litter and dead wood (stem wood, branches, needles/leaves and stumps and coarse/fine roots) on the soil layer and their decay consequently affect the amount of soil organic matter and nitrogen availability for growth. Atmospheric nitrogen deposition of 10 kg N $ha^{-1}$ (observed long term mean in Finland) was used in model simulations (Järvinen and Vänni 1994; Kellomäki et al. 2005).

In our simulations, management control included artificial regeneration (planting) with the desired spacing and tree species, control of stand density in tending of seedling stand and in thinning, and final cut. In harvesting, we considered only timber (saw log and pulp wood). The model simulations with a time step of one year were carried out 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). Each simulation case was repeated 20 times and the mean values of each output variable were used in data analyses. This was undertaken as 10–20 iterations will be sufficient to stabilize the mean values based on our analysis (the coefficient of variation was 1.6% for 20 iterations over 90-year period in total stem volume at plot level). Previous model validation (Kellomäki et al. 2008; Routa et al. 2011a, b) has also shown good agreement with the measured volume growth of the main Finnish tree species in the National Forest Inventory plots throughout Finland. Also, simulated volume growth by the SIMA model and the empirical growth and yield model Motti (Hynynen et al. 2002) has shown good agreement (Kellomäki et al. 2008; Routa et al. 2011a, b, 2012).

## 2.2 Forest conservation and management scenarios used in model simulations

We simulated the development of stem volume growth, harvested amount of timber, carbon stock (soil and trees) and amount of dead wood of forests on 10$^{th}$ National Forest Inventory plots (in total 2642 plots) on upland mineral soils throughout Finland under a changing climatic and management conditions over 2010–2099. In all, upland forests cover 67 % of total forest area in Finland and peatland forests 33 % (Finnish Statistical Yearbook of Forestry 2014). Our results are the most applicable for upland forests. However, they may also be in general applicable with reservation for well drained peatlands with similar site fertility (excluding carbon in soil).

In the simulations, we applied three alternative forest conservation scenarios and thinning regimes (Table 1). In the baseline conservation scenario, we left 10–30 % of forest inventory plots from central to northern Finland outside management (Table 1), unlike in southern Finland where current forest conservation area is very low (2%) (Finnish Statistical Yearbook of Forestry 2014). As a result, the predicted volume growth, volume of growing stock and harvested amount of timber in the first period 2010–2039 were under the current climate in good agreement with the forest statistics for the period of 2004–2008 (Finnish Statistical Yearbook of Forestry 2014). In other forest conservation scenarios, we increased conservation area by 10% and 20% throughout Finland compared to the baseline conservation BC.

In managed forests in Finland, mostly smaller/suppressed trees are removed in thinning from below, and the timing and intensity of thinnings are determined by and dominant height and basal area (i.e. the cross-sectional area of stems of all trees in a stand) thresholds specific to site fertility type, tree species and region. The baseline thinning regime BT (0, 0) follows the current Finnish forest management recommendations (Äijälä et al. 2014). In other regimes, the upper and lower basal area limits were kept 20% higher or lower, which either delayed or resulted in earlier thinnings and higher/lower stocking and number of thinnings over a rotation. The timing of final felling was determined by the basal area weighted diameter at breast height; it varied depending on tree species, site fertility type and region (22–30 cm).

Compared to the current Finnish forest management recommendations, large variation exists in practice in timing and intensity of forest management measures (Finnish Statistical yearbook of Forestry 2014). Thus, in thinnings and final fellings, a mean delay of 13 years was also used in this study. Furthermore, in the simulations the clear-cut area was always planted with the same tree species that dominated the site before the final felling, using 2000 seedlings per hectare for Norway spruce and Scots pine and 1600 seedlings per hectare for silver birch. In addition to planting, Scots pine, Norway spruce and birch seedlings were born on the sites naturally. Tending of seedling stand was also carried out before the first commercial thinning.  Currently, about 64% of regenerated area is planted in Finland, 18% sown, and 18% established using natural regeneration (Finnish Statistical yearbook of Forestry 2014). Thus, the management scenarios applied here have some differences compared to the "business as usual in actual Finnish forestry".

**2.3 Climate scenarios used in model simulations**

The current climate data are based on measurements by the Finnish Meteorological Institute (FMI) for temperature and precipitation during the reference period 1981–2010. The observational data were interpolated onto a 10 km × 10 km grid throughout Finland (Venäläinen et al. 2005; Aalto et al. 2012). For changing climatic conditions, we used climate data representing two future representative greenhouse gas concentration pathways: RCP4.5 and the RCP8.5 (van Vuuren et al. 2011). The former represents the atmosphere characterized relatively successful mitigation of greenhouse gas emissions; the latter the atmosphere with no efficient mitigation activities applied. The RCP4.5 and the RCP8.5 climate scenario data used here were downloaded from the Coupled Model Intercomparison Project phase 5 (CMIP5) database (WCRP 2011; Taylor et. al. 2012), and represent a mean of 28 different climate models aimed to obtain the best estimate of the change. These datasets comprised the projected change of monthly mean temperatures and precipitation for future periods (2010–2039, 2040–2069, and 2070–2099). Also the climate change data were interpolated by FMI onto the 10 km × 10 km grid as the observational data.

Based on these RCP4.5 and RCP8.5 climate change projections, the mean temperature is expected to increase in Finland by about 3–5°C and precipitation by about 7–11 % during the potential growing season (April to September) by 2100. Meanwhile, temperature is expected to increase by 3–6°C and precipitation by 10–20 % during the dormancy season (October-March) by the end of the 21$^{th}$ Century. The atmospheric $CO_2$ concentration increased from the current climate 360 ppm to 532 ppm and 807 ppm under the RCP4.5 and the RCP8.5 scenarios, by 2071–2100 (van Vuuren et al. 2011).

**2.4 Data analyses**

For each simulation, the mean annual stem volume growth ($m^3$ $ha^{-1}$ $a^{-1}$), harvested amount of timber ($m^3$ $ha^{-1}$ $a^{-1}$), carbon stock (in soil and trees, Mg $ha^{-1}$) and quantity of dead stem wood (standing and on the ground, $m^3$ $ha^{-1}$) were calculated for each 30-year period. Based on these data, we studied how the use of alternative forest conservation areas and thinning regimes affected the development of volume growth, harvested amount of timber, carbon stock and quantity of dead wood from southern to northern Finland under changing climatic conditions for the periods 2010–2039, 2040–2069, and 2070–2099. We analyzed especially the relative effects of changing climate and/or forest management scenarios on the studied variables, using as a baseline the current climate with the baseline management and baseline conservation (BT (0,0) – BC). However, the initial amount of dead wood was not available in forest inventory data used as input for the SIMA model simulations, which explains the clearly lower values of dead wood quantity in the first 30-year period compared to other periods. Despite this, still comparison between the management and conservation regimes in a certain period was appropriate. The current version of SIMA model could not either use the initial amount of deadwood as input in simulations.

## 3. Results

### 3.1 Volume growth

Under the current climate, the mean annual volume growth increased under the baseline conservation scenario and thinning regime (BT (0, 0) – BC) in southern Finland from 5.8 to 7.0 $m^3\ ha^{-1}a^{-1}$ and in northern Finland from 2.8 to 3.3 $m^3\ ha^{-1}\ a^{-1}$ from the first to the last 30-year period (Figure 1). The simultaneous use of 20% higher forest conservation area and stocking in thinning (BT (+20, +20) – BC+20%) increased volume growth the most both in northern and southern Finland compared to the BT (0,0) – BC (Figure 2), i.e. up to 14% in the second 30-year period. However, the maintenance of 20% lower stocking in thinning (BT (-20, -20)) also increased it, i.e. up to 11% in the second 30-year period, when the same conservation scenario was applied. On the other hand, the simultaneous use of 20% higher conservation area and 20% lower stocking in thinning reduced volume growth up to 4% in the last 30-year period in southern Finland under the current climate, compared to the BT (0,0) –BC.

Under the changing climate with the RCP4.5 scenario, volume growth increased both in the second and the third 30-year period up to 23% in southern Finland and up to 70% in northern Finland compared to current climate. Under the RCP8.5 scenario, it increased by up to 91% in northern Finland in the second 30-year period and decreased by up to 14% in southern Finland in the last 30-year period. Under the changing climate, the change of conservation area and/or stocking level in thinning affected volume growth in the first and second 30-year periods in a relative sense less than under the current climate.

Figure 1.

Figure 2.

**3.2 Harvested amount of timber**

Under the current climate, the mean annual harvested amount of timber decreased under the baseline conservation scenario and thinning regime (BT (0, 0) – BC) in southern Finland from 4.3 to 4.2 $m^3$ $ha^{-1}$ $a^{-1}$ and in northern Finland from 1.8 to 1.5 $m^3$ $ha^{-1}$ $a^{-1}$ from the first to the last 30-year period. It decreased the most, up to 37% and 50% in southern and northern Finland, respectively, in the first 30-year period compared to the BT (0,0) – BC, when forest conservation area was increased by 20% and stocking was kept at the same time 20 % higher in thinning (BT (20, 20) – BC+20) (Figure 2). However, when stocking was kept 20 % lower in thinning BT (-20, -20), and the baseline conservation scenario applied, the amount of timber increased up to 17% in southern Finland in the last 30-year period. It also increased in northern Finland. However, the simultaneous increase of conservation area and maintenance of lower stocking in thinning (BT (-20,-20)) resulted in the second 30-year period up to 34% lower amount of timber both in southern and northern Finland compared to the BT (0,0) – BC. Overall, when the BT (-20, -20) was used, most of the thinnings were carried out in the first and the third 30-year periods; the opposite to with BT (20, 20). In addition, the change of conservation area affected the harvested amount of timber clearly more than the thinning regime did under the current climate.

Under the changing climate, the harvested amount of timber was for the same management regime in southern Finland up to 18% lower under the RCP8.5 than under the current climate, and up to 151% higher in northern Finland, respectively. Under the warming climate, the increase of conservation area and simultaneous change in stocking level in thinning affected the harvested amount of timber in a similar way as under the current climate.

The share of harvested amount of timber of total volume growth also largely depended on the conservation scenario and thinning regime applied (Figure 3). In the first 30-year period, it ranged under the current climate in southern Finland from 43–86 %, being lowest in the BT (20, 20) –

BC+20% and largest in the BT (-20, -20) – BC. In the last 30-year period, the corresponding values were 45% and 73%. In northern Finland, the share of harvested amount of timber from total volume growth ranged in the first 30-year period from 30–75 %, also being the lowest and the largest under the same management regimes than in southern Finland. In the last 30-year period the corresponding values were 34% and 49%. Under the changing climate, the share of harvested amount of timber of total volume growth increased in northern Finland, unlike in southern Finland, for most of the management scenarios in the last 30-year period, ranging from 42–62% under RCP8.5.

Figure 3.

### 3.3 Forest ecosystem carbon stock

Under the current climate, the mean annual forest ecosystem carbon stock (trees and soil) increased under the baseline conservation scenario and thinning regime (BT (0, 0) – BC) in southern Finland from 79 to 87 Mg ha$^{-1}$ and in northern Finland from 72 to 88 Mg ha$^{-1}$ from the first to the last 30-year period (Figures 4 and 5). When the forest conservation area was increased by 20% and stocking was kept 20% higher in thinning (BT (+20, +20) – BC+20%) compared to the BT (0,0) –BC, the carbon stock increased up to 38% in southern Finland in the second and the last 30-year periods (Figures 4 and 5). When stocking was kept 20% lower in thinning and baseline conservation scenario applied (BT (-20, -20) – BC), the carbon stock decreased up to 6% in the first 30-year period in southern Finland compared to the BT (0,0)-BC. However, it increased up to 27 % in the second and the last 30-year periods in southern Finland when the conservation area was increased by 20% (BT (-20, -20) – BC+20).

Under the changing climate with the RCP4.5 and RCP8.5, change of conservation area and/or stocking level in thinning affected the carbon stock in a similar way as under the current climate. In general, climate change increased the carbon stock the most, up to 26% in the last 30-year period in northern Finland, due to the simultaneous increase of volume growth. However, the carbon stock decreased up to 19% in southern Finland in the last 30-year period under the RCP8.5 due to the reduced growth. Change of conservation area affected the carbon stock more than the change of stocking level in thinning, regardless of climatic conditions.

Figure 4.

Figure 5.

### 3.4 Amount of dead wood

Under the current climate, the mean annual amount of dead wood was under the baseline conservation scenario and thinning regime (BT (0, 0) – BC) 3.7 $m^3 ha^{-1}$ in southern Finland and 1.7 $m^3 ha^{-1}$ in northern Finland in the last 30-year period (Figure 5). The increase of forest conservation area by 20% and maintenance of 20% higher stocking in thinning (BT (+20, +20) – BC+20%) compared to the BT (0, 0) – BC, increased the amount of dead wood up to 21% in the last 30-year period in northern Finland. However, it increased up to 20 % also if lower stocking was maintained in thinning, due to the increase of logging residues on forest soil. Under the changing climate, the amount of dead wood was, in the last 30-year period in northern Finland, up to 146% and in southern Finland up to 57% higher compared to the current climate. Under the changing climate, the increase of conservation area and/or maintenance of higher stocking in thinning compared to the BT (0, 0) – BC affected the amount of dead wood in a similar way as under the current climate.

## 4. Discussion and Conclusions

We used a forest ecosystem model to study how changes in forest conservation area affected volume growth, harvested amount of timber, carbon stock and the quantity of dead wood in Finnish forests, while using different thinning regimes in managed forests. We conducted the analysis over the period 2010–2099 under current climate and future climate change predicted for Finland by the RCP4.5 and RCP8.5 scenarios. Under the current climate, an increase of forest conservation area resulted in larger volume growth, carbon stock (in soil and trees) and quantity of dead wood, but decreased the harvested amount of timber. However, under the warming climate, it decreased the long-term volume growth in southern Finland the most with the RCP8.5 scenario. Our work showed clearly that there are trade-offs for production of different ecosystem services like carbon stock in the forest and the harvested amount of timber, having implications also for carbon in harvested wood products. This was also found in previous studies (Seely et al. 2002; Matala et al. 2009; Hynynen et al. 2015; Triviño et al. 2015).

The maintenance of 20% lower or higher growing stock in thinning, compared to the baseline thinning regime affected volume growth, carbon stock and amount of timber less than any increase in conservation area. Maintenance of higher stocking delayed thinnings and decreased their number compared to the baseline thinning regime. This was the opposite to the maintenance of lower growing stock in thinning, which affected the results in different 30-year periods. Maintenance of 20% lower growing stock in thinnings could not compensate for the decrease of harvested amount of timber caused by the increase of forest conservation area. It also increased the amount of dead wood due to higher thinning frequency and increase of non-harvested small-sized stem wood (including tree tops) on ground. When using increased conservation area scenarios, more intensive forest management than used in our study, such as increased forest fertilization, improved seedling stock, or shorter rotation lengths, would be needed in managed forests, to maintain sufficient forest biomass production for forest bioeconomy.

The amount of the harvested timber was 43–86 % of total stem volume growth in southern Finland and 30–75 % of that in northern Finland, depending on the period, the management regime and the climate scenario. As a comparison, in 2013 about 54 % of the annual volume growth of 104 million $m^3$ was harvested as timber in Finland, in southern Finland 64 % and in northern Finland 39 % (with energy wood 63, 75 and 45 %, respectively) (Finnish Statistical Yearbook of Forestry 2014). Climate warming, particularly the RCP8.5 scenario increased volume growth, carbon stock and the harvested amount of timber relatively more in northern Finland, where current growth of forests is limited by the short growing season and low temperatures (Mäkinen et al. 2000, 2002; Briceño-Elizondo et al. 2006). However, in northern Finland the absolute volume growth remains still lower than in southern Finland. In southern Finland, the observed reduction in growth under the warming climate could be mainly explained by differences in tree species-specific responses to climate warming and water availability (Torssonen et al. 2015). Previous studies (Mäkinen et al. 2001; Ge et al. 2013a, b) have also reported reduced growth of Norway spruce with shallow rooting in southern Finland, especially for sites with low water holding capacity. In our work, climate warming also increased the amount of dead wood throughout Finland, and the most in southern Finland. The share of standing deadwood of the total amount of deadwood (standing and on the ground) ranged from 11–29 % in southern Finland and from 7–28 % in northern Finland in the last 30-year period, depending on the management scenario and climate applied (results not shown in detail). Because the initial amount of dead wood was not available in forest inventory data, the comparison of dead wood quantity between periods was not possible.

Regional differences in the responses of forests to changing climate and management were also strongly affected by the initial forest structure (age and tree species dominance). At the beginning of the simulation, there were more old forests in northern Finland relative to southern Finland (Finnish Statistical yearbook 2014). In northern Finland, a large share of forest area was under forest conservation regardless of conservation scenario applied and the forests were dominated by Scots pine. Conversely, in southern Finland, the growth was at higher level and the forests were dominated by Norway spruce. From the climate change mitigation point of view, increased carbon sequestration as a consequence of increased conservation area would seemingly provide an instant and cost-efficient mean for emission reduction, especially in southern Finland. However, according to our results, the most severe warming decreased the carbon sequestration potential, decreasing also climate benefits in the long run. Increasing the growing stock means also more volume at risk of disturbances including forest fires, insects, pathogens and wind/snow extremes (Päätalo et al. 1999; Zeng et al. 2007; Peltola et al. 2010), which are all expected to increase under the warming climate (IPCC 2013). In addition, an  increase in setting aside forests would result in economic losses for forest owners due to a decrease in timber harvest, which would call for voluntary conservation agreements and compensating economic losses for forest owners (Mönkkönen et al. 2009, 2014; Öhman et al. 2011; Triviño et al. 2015).

Decreased timber harvest would also decrease the mitigation potential of the forests since less wood based material and energy would be available for substitution of fossil based materials and energy. However, climate change mitigation impacts were not in the main focus of our study nor calculated. Also increasing climatic risks should be taken into account in future studies, as they may greatly affect sustainability of forest management and forestry, and production of various forest ecosystem services (Kellomäki et al. 2005; Peltola et al. 2010, Gregow et al. 2011; Seidl et al. 2011; Subramanian et al. 2016).

To conclude, the increase of forest conservation area results, in general, in higher carbon stock in forests but a lower amount of forest biomass available for the bioeconomy and, respectively, for subsitituting fossil based materials and fuels. In this sense, more intensive management, e.g. the use of improved seed/seedling material in regeneration (with better growth), site-specific preference of better growing tree species and spacing, heavier or more frequent thinning, nitrogen fertilization and shorter rotations, would be needed in managed forests to compensate for the decrease in the harvested amount of timber due to the increase of forest conservation area. However, wood production and carbon sequestration and stocks of forests over time are also greatly affected by the current forest structure (age and species) and prevailing climatic conditions (Garcia-Gonzalo et al. 2007; Kellomäki et al. 2008), which should also be taken into account when adapting management and utilization (e.g. for substituting fossil resources) of forest resources for different ecosystem services under the projected climate change, and to mitigate climate change.

**Acknowledgments**

This work was supported by the ADAPT project (14907) and the strategic research project FORBIO (14970), led by prof. Heli Peltola and funded by the Academy of Finland. It was also supported by the university of Eastern Finland. The national forest inventory data obtained from the Natural Resources Institute Finland and climatic data (for current and changing climate scenarios) obtained from the Finnish Meteorological Institute, and especially Kimmo Ruosteenoja, are acknowledged.

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| Short name | Description |
|---|---|
| BT (0, 0) – BC | BT(0,0): Baseline thinning regime with BC: baseline conservation scenario, in which 10% of forest inventory plots were left in old Forest Center unit FC 10, 20% in FC 11–12 and 30 % in FC 13 outside management. The probability to be left randomly outside management, and thus used for conservation, increased for forest inventory plots as a function of their basal area |
| BT (20, 20) – BC | BT(20,20): 20 % higher basal area thresholds for thinning compared to BT(0,0) with BC |
| BT (-20, -20) – BC | BT(-20,-20): 20 % lower basal area thresholds for thinning compared to BT (0,0) with BC |
| BT (0, 0) – BC+10 | BT(0,0) with BC+10: 10% increase of forest conservation area compared to BC |
| BT (20, 20) – BC+10 | BT(20,20) with BC+10 |
| BT (-20, -20) – BC+10 | BT(-20,-20) with BC+10 |
| BT (0, 0) – BC+20 | BT(0,0) with BC+20 |
| BT (20, 20) – BC+20 | BT(20,20) with BC+20 |
| BT (-20, -20) – BC+20 | BT(-20, -20) with BC+20 |

**Figure captions**

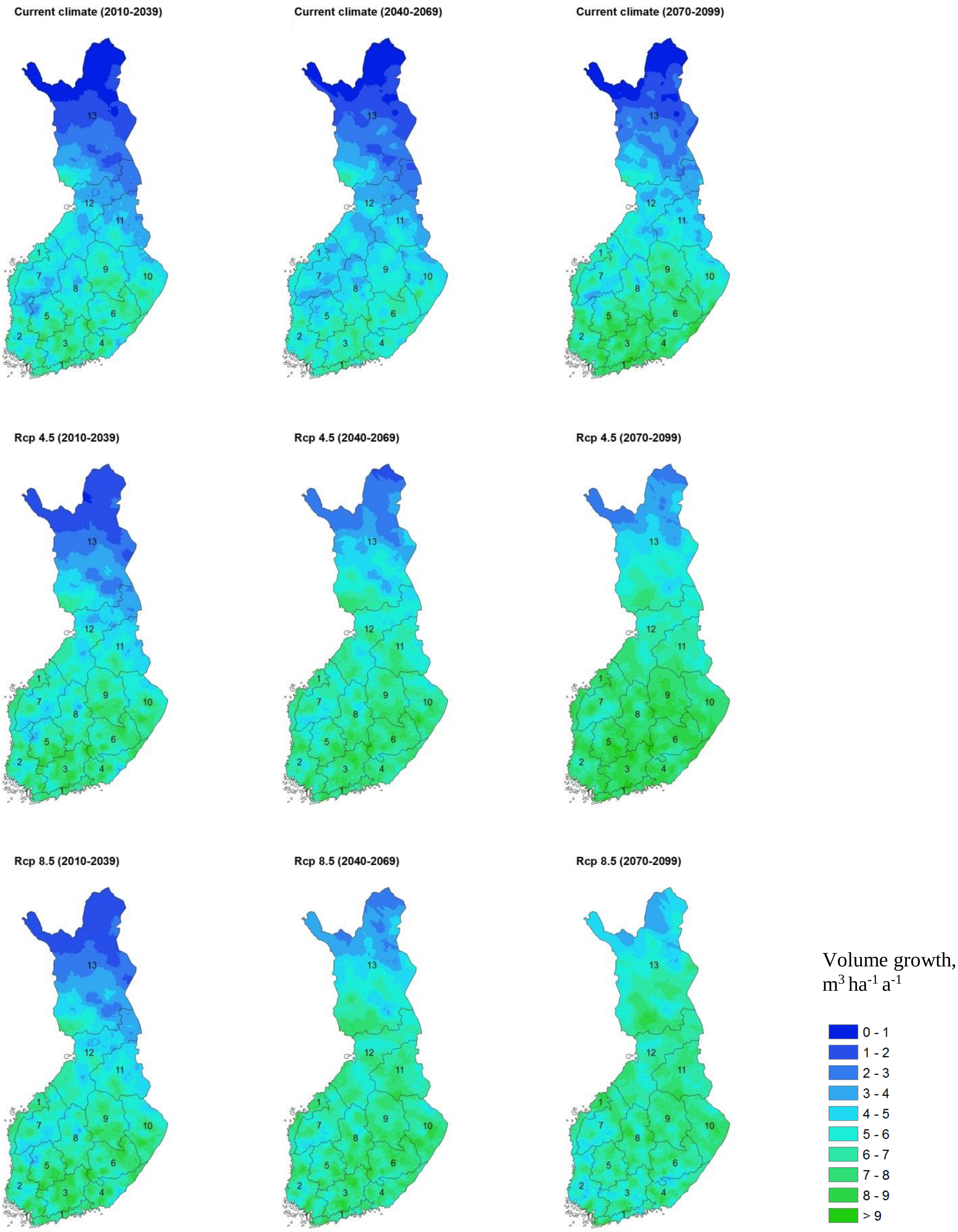
**Figure 1.** Mean annual volume growth ($m^3$ $ha^{-1}$ $a^{-1}$) throughout Finland over three 30-year simulation periods under the baseline conservation and thinning regime (BT (0, 0) – BC) under the current climate (CU) and the RCP4.5 and the RCP8.5 climate change projections. Legends for numbers (i.e. old forest center units): Southern Finland: 1–6, Central Finland: 7–10 and Northern Finland: 11–13.

**Figure 2.** The mean annual volume growth ($m^3$ $ha^{-1}$ $a^{-1}$) and harvested amount of timber ($m^3$ $ha^{-1}$ $a^{-1}$) for different conservation scenarios and thinning regimes under the current climate (CU) and RCP4.5 and RCP8.5 climate change projections in southern and northern Finland over three 30-year simulation periods.

**Figure 3**. The share of harvested timber of total volume growth (%) for different conservation scenarios and thinning regimes under the current climate (CU) and RCP4.5 and RCP8.5 climate change projections in southern and northern Finland over three 30-year simulations periods.

**Figure 4.** Mean annual carbon stock in soil and trees (Mg $ha^{-1}$) throughout Finland over three 30-year simulation periods under the baseline conservation and thinning regime (BT (0, 0) – BC) under the current climate (CU) and the RCP4.5 and the RCP8.5 climate change projections. Legends for numbers (i.e. old forest center units): Southern Finland: 1–6, Central Finland: 7–10 and Northern Finland: 11–13.

**Figure 5**. The mean annual carbon stock in soil and trees (Mg $ha^{-1}$) and amount of dead stem wood ($m^3$ $ha^{-1}$) for different conservation scenarios and thinning regimes under the current climate (CU) and RCP4.5 and RCP8.5 climate change projections in southern and northern Finland over three 30-year simulation periods. The initial amount of dead wood was not available in the forest inventory data used as an input for the SIMA model simulations, which explains the low values in the first 30-year period.



Current climate (2010-2039)
Current climate (2040-2069)
Current climate (2070-2099)
Rcp 4.5 (2010-2039)
Rcp 4.5 (2040-2069)
Rcp 4.5 (2070-2099)
Rcp 8.5 (2010-2039)
Rcp 8.5 (2040-2069)
Rcp 8.5 (2070-2099)
Volume growth, m3 ha-1 a-1
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
> 9


**Figure 1.**

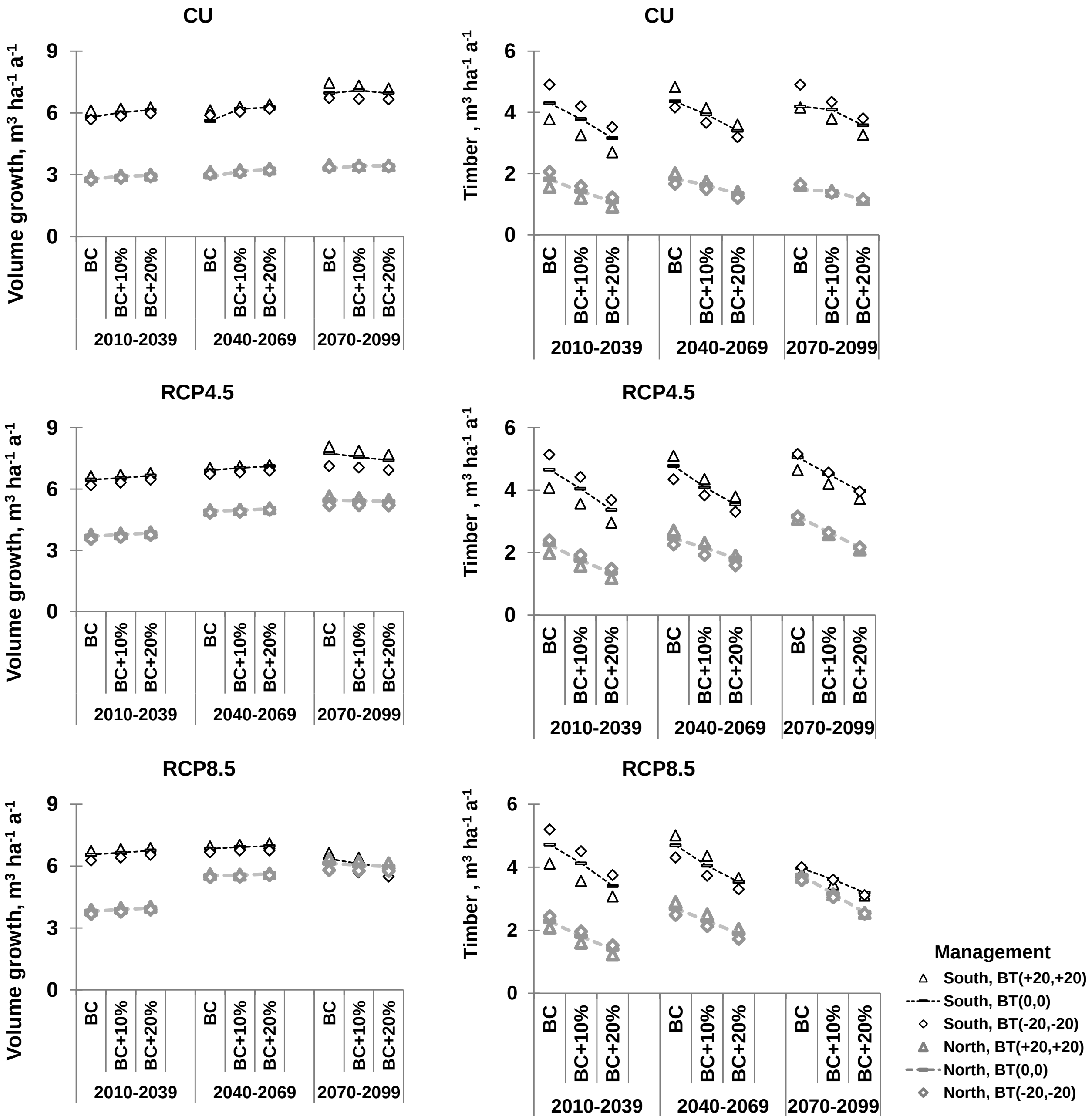

CU
Volume growth, m³ ha⁻¹ a⁻¹
Timber , m³ ha⁻¹ a⁻¹
RCP4.5
RCP8.5
BC
BC+10%
BC+20%
2010-2039
2040-2069
2070-2099
Management
South, BT(+20,+20)
South, BT(0,0)
South, BT(-20,-20)
North, BT(+20,+20)
North, BT(0,0)
North, BT(-20,-20)

**Figure 2.**

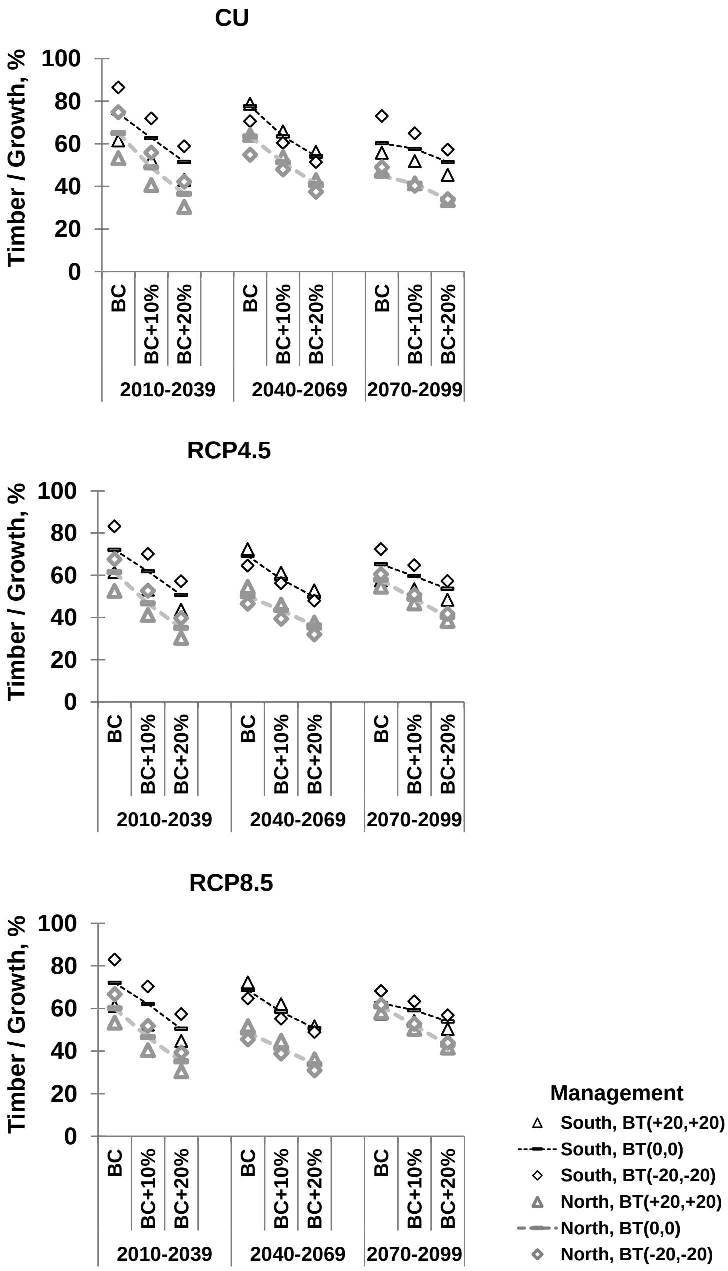

CU
RCP4.5
RCP8.5
Timber / Growth, %
100
80
60
40
20
0
BC
BC+10%
BC+20%
2010-2039
2040-2069
2070-2099
Management
South, BT(+20,+20)
South, BT(0,0)
South, BT(-20,-20)
North, BT(+20,+20)
North, BT(0,0)
North, BT(-20,-20)

**Figure 3.**

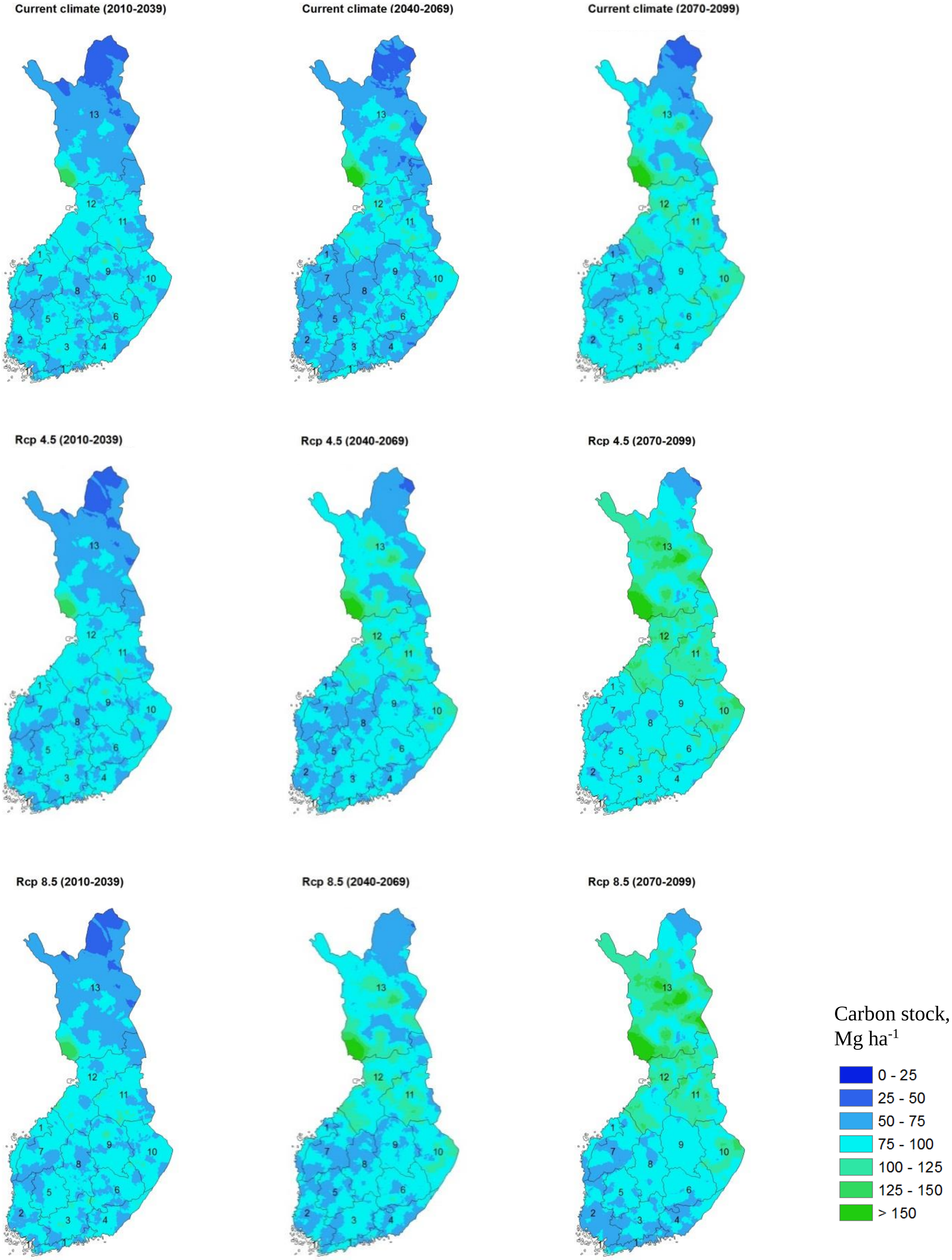

Current climate (2010-2039)
Current climate (2040-2069)
Current climate (2070-2099)
Rcp 4.5 (2010-2039)
Rcp 4.5 (2040-2069)
Rcp 4.5 (2070-2099)
Rcp 8.5 (2010-2039)
Rcp 8.5 (2040-2069)
Rcp 8.5 (2070-2099)
Carbon stock, Mg ha-1
0 - 25
25 - 50
50 - 75
75 - 100
100 - 125
125 - 150
> 150

**Figure 4.**

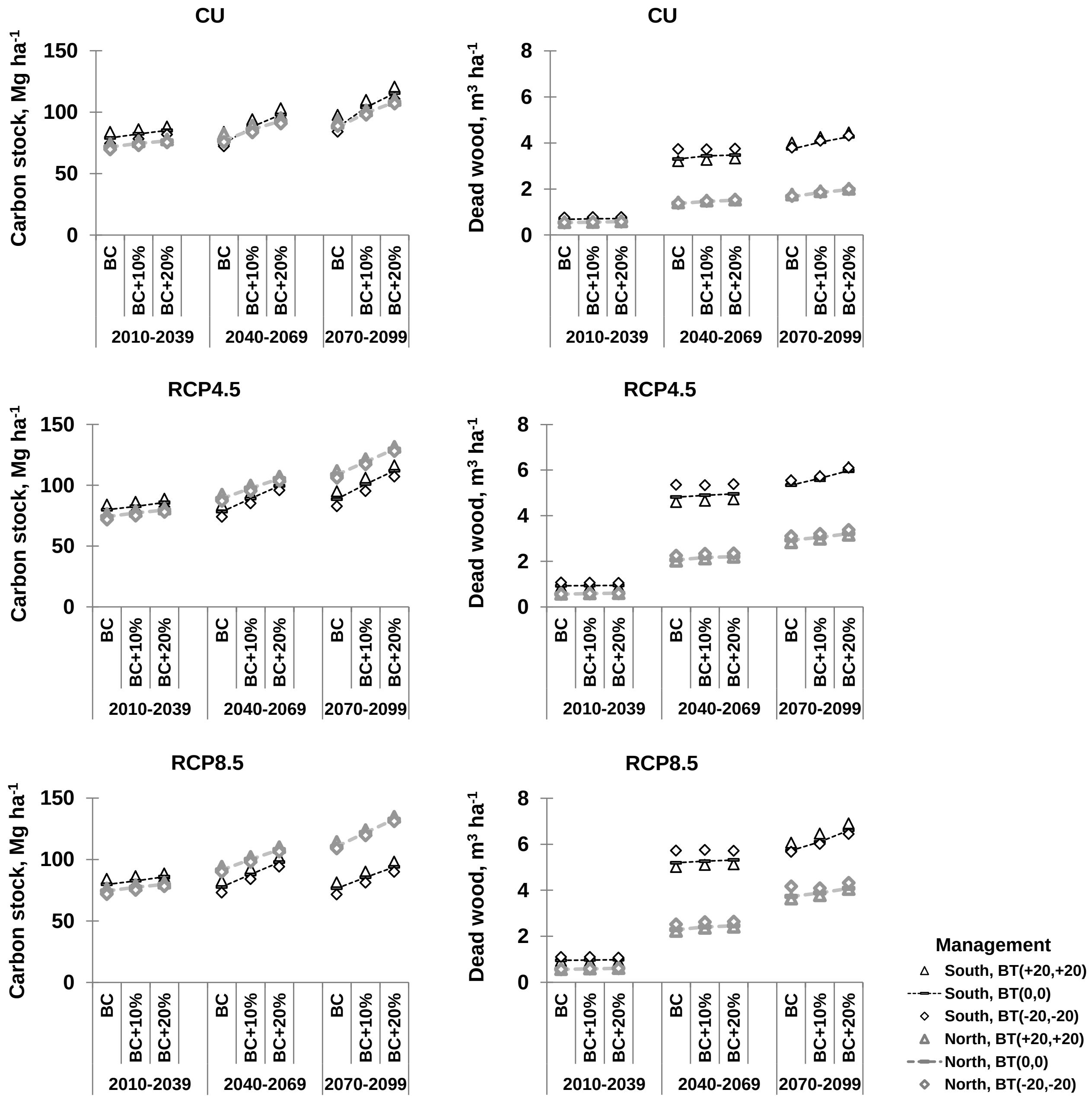

CU
Carbon stock, Mg ha-1
Dead wood, m3 ha-1
RCP4.5
RCP8.5
BC
BC+10%
BC+20%
2010-2039
2040-2069
2070-2099
Management
South, BT(+20,+20)
South, BT(0,0)
South, BT(-20,-20)
North, BT(+20,+20)
North, BT(0,0)
North, BT(-20,-20)

**Figure 5.**