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Scenario analyses on the effects of forest management and CMIP5 climate projections on timber production and carbon stocks of upland boreal forests in Finland

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Academic dissertation

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ABSTRACT

This study employed scenario analyses to evaluate the effects of forest management and different CMIP5 climate projections on timber production and carbon stocks of upland boreal forests in Finland. The forest ecosystem model simulations were conducted over a 90-year period from the stand to regional level by using both model stand data (Paper I) and national forest inventory data (Papers II-III). In simulations, it was employed data from the current climate and several CMIP5 projections (multi-model means and individual climate model runs) under the RCP4.5 and RCP8.5 forcing scenarios. More specifically, it was studied the impacts of different climate projections and thinning regimes (Papers I and III), tree species preferences in forest regeneration (Paper II) and forest conservation scenarios (Paper III) on volume growth, carbon stocks and timber production (Papers I-III), economic profitability (Paper I), and the amount of deadwood of forests (Paper III).

The effects of different climate projections on volume growth, carbon stocks, timber production and its economic profitability and the amount of deadwood varied largely, depending on geographical region, tree species, and severity of climate change. The degree of differences in the responses of tree species and boreal regions increased with the severity of climate change (Papers I-III). Regardless of the tree species, the positive impacts of climate change were larger in the north. In the south, Silver birch benefitted most from the climate change projections and the most under severe climate change. This was unlike Norway spruce and also partially, Scots pine (Papers I-II). An increase in forest conservation area increased volume growth, carbon stock, and the amount of deadwood in forests, unlike timber production. Depending on boreal region, tree species, and severity of climate change, different adaptive forest management measures would be needed to utilize the positive impacts of climate change and to minimize harmful ones.

Keywords: conservation scenarios, deadwood, forest ecosystem model, RCPs, timber production, tree species preference

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Last but not the least, I dedicate this endeavor to the soul of my father and the souls of my sisters, Hadeel and Dania, who have left this world unexpectedly and left behind them also so much tears and sorrow in our hearts. May Allah bless them and may their souls rest in peace and mercy.

Joensuu, October 2018

Laith ALRahahleh

LIST OF ORIGINAL ARTICLES

This thesis is based on the following three published articles, which are referred to in the text by their Roman numerals (i.e., Papers I, II and III). All articles are reprinted with the kind permission of the publishers or with the right retained as author.

I. ALRahahleh L., Kilpeläinen A., Ikonen V.-P., Strandman H., Venäläinen A., Peltola H. (2018). Effects of CMIP5 projections on Volume growth, Carbon stock and Timber yield in managed Scots pine, Norway spruce and Silver birch stands under southern and northern Boreal condition. Forests 9(4): 208. 21p. http://doi.org/10.3390/f9040208

II. ALRahahleh L., Kilpeläinen A., Ikonen V.-P., Strandman H., Asikainen A., Venäläinen A., Kaurola J., Kangas J., Peltola H. (2018). 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. European Journal of Forest Research 137(5):573-591. https://doi.org/10.1007/s10342-018-1126-z

III. ALRahahleh L., Ikonen V.-P., Kilpeläinen A., Torssonen P., Strandman H., Asikainen A., Kaurola J., Venäläinen A., Peltola H. (2017). 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. Canadian Journal of Forest Research 47(2): 215-225. https://doi.org/10.1139/cjfr-2016-0153

This study was jointly designed by Laith ALRahahleh and Heli Peltola. ALRahahleh had the main responsibility for the simulations, analyzing the results and writing of articles (Articles I-III). The implementation of simulations were supported by Veli-Pekka Ikonen. Co-authors commented on the manuscripts.

TABLE OF CONTENT

ABBREVIATIONS AND DEFINITIONS

Symbol	**Definition**
CanESM2 RCP4.5	Global climate model (GCM), developed by the Canadian Center for Climate Modelling and Analysis, Canada, with a radiative force of 4.5 W/m^2 by the end of 2100
CanESM2 RCP8.5	Global climate model (GCM), developed by the Canadian Center for Climate Modelling and Analysis, Canada, with a radiative force of 8.5 W/m^2 by the end of 2100
CMIP5	The Couple Model Intercomparison Project phase 5 database
CMIP3	The Couple Model Intercomparison Project phase 3 database
CNRM-CM5 RCP8.5	Global climate model (GCM), developed by the National Center for Meteorological Research, France, with a radiative force of 8.5 W/m^2 by the end of 2100
CO_2	Carbon dioxide
CU	Current climate (CU, for the period 1981-2010)
d.d	Degree days (TS > +5)
Energy wood	Stem diameter < 6 cm
EU	European Union
FMI	Finnish Meteorological Institute
GCM	Global Climate Model
GFDL-CM3 RCP8.5	Global climate model (GCM), developed by National Oceanic and Atmospheric Administration (NOAA), USA, with a radiative force of 8.5 W/m^2 by the end of 2100
HadGEM2-ES RCP4.5	Global climate model (GCM), developed by the Hadley Center for Climate Prediction and Research, UK, with a radiative force of 4.5 W/m^2 by the end of 2100
HadGEM2-ES RCP8.5	Global climate model (GCM), developed by the Hadley Center for Climate Prediction and Research, UK, with a radiative force 8.5 W/m^2 by the end of 2100

MIROC5 RCP4.5	Global climate model (GCM), developed jointly by Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan, with a radiative force of 4.5 W/m^2 by the end of 2100
MIROC5 RCP8.5	Global climate model (GCM), developed jointly by Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan, with a radiative force of 8.5 W/m^2 by the end of 2100
Mean RCP4.5	Mean climate projections of 28 GCMs with radiative force of 4.5 W/m^2 by the end of 2100
Mean RCP8.5	Mean climate projections of 28 GCMs with a radiative force of 8.5 W/m^2 by the end of 2100
MPI-ESM-MR-RCP8.5	Global climate model (GCM), developed by Max Planck Institute for Meteorology, Germany, with a radiative force of 4.5 W/m^2 by the end of 2100
MPI-ESM-MR-RCP8.5	Global climate model (GCM), developed by Max Planck Institute for Meteorology, Germany, with a radiative force of 8.5 W/m^2 by the end of 2100
MOTTI	Statistical growth and yield model developed at the National Resources Institute, Finland
NFI	National Forest Inventory
NPV	Net present value
SIMA	A gap-type forest ecosystem model developed at the University of Eastern Finland
Timber	Sawlog and pulpwood
TS	Temperature sum
TSopt	Optimum temperature sum
TSmin	Minimum temperature sum
TSmax	Maximum temperature sum

1 INTRODUCTION

1.1 Impacts of forest management and climate change on Finnish forests and forestry

Finland is one of Europe's most densely forested countries with 26.2 million hectares of forested land, where about 90% of forest area is assigned for timber production. In recent decades, the annual increment of the volume of growing stock (e.g., 104 million cubic meter a^{-1}, in 2013) has exceeded the annual round wood harvest (e.g., in 2004-2013, about 60 million m^3, see Finnish Statistical Yearbook 2014). However, there is pressure to increase volume growth in Finnish forests to both accomplish the bioeconomy and climate change mitigation targets (Ministry of Employment and the Economy 2014; COM/2014/0015 2014). In this context, 10-30 million m^3 of additional forest biomass supply is needed to meet the bioeconomy targets, where approximately 55% of the biomass supply is predicted to originate from forests (Ministry of Employment and the Economy; Scarlat et al. 2015). This would also create new opportunities for forest owners to boost the economic profitability of forestry. In addition to wood production, there are also other ecosystem services, such as carbon sequestration, maintenance of biodiversity, and recreational values of forests that should be safeguarded and considered in sustainable forest management strategies. The recent EU Parliament resolution also clearly calls for considerable measures to sustain and maintain forest biodiversity in European forests (EU Parliament 2016). One of the main drivers of forest conservation in Finland is the small amount of deadwood in managed forests and the shrinking area of old-growth forests (Rassi et al. 2010).

Nowadays, the growth of boreal forests in northern Europe is limited by a relatively short growing season, low summer temperatures, and limited supply of nutrients (see e.g., Briceño-Elizondo et al. 2006 a, b; Hyvönen et al. 2007; Kellomäki et al. 2008). Yet, under a gradually changing climate, forest growth is predicted to increase in Nordic countries, including Finland (see e.g., Saxe et al. 2001; Bergh et al. 2003; Hyvönen et al. 2007; Kellomäki et al. 2008; Linder et al. 2010; Poudel et al. 2011, 2012). This is because of lengthening of growing season and warmer conditions, which subsequently increase the decay of soil organic matter and the supply of nutrients available for growth, respectively (see e.g., Saxe et al. 2001; Hyvönen et al. 2007). Likewise, elevation of the atmospheric CO_2 concentration would further enhance forest growth (see e.g., Peltola et al. 2002; Ellsworth et al. 2012; Kellomäki et al. 2018). As a result of an increase in forest growth, also timber production and carbon stock of boreal forests may increase under a changing climate (see e.g., Kellomäki et al. 2008; Lindner et al. 2010; Poudel et al. 2011, 2012).

The severe climate warming and associated increase in drought events may make the current growing conditions suboptimal for some tree species and more optimal for others (see e.g., Kellomäki et al. 2008, 2018; Allen et al. 2010; Lindner et al. 2010, 2014; Kolström et al. 2011; Granda et al. 2013; Taeger et al. 2013; Schäfer et al. 2017). Currently, the growing conditions in southern Finland are near optimum, especially for Norway spruce (*Picea abies* (L.) Karst.), and partially for Scots pine (*Pinus sylvestris* L). The responses of different tree species to climate change and extreme weather events may differ largely, depending on the geographical region and the severity of climate change (Kellomäki et al. 2008; Granda et al. 2013; Torssonen et al. 2015). For instance, under severe climate change associated with increasing drought episodes, the growth of cold-adapted species, particularly Norway spruce with its shallow rooting system, may decline, especially on sites where water availability is limited (see e.g., Kellomäki et al. 2001, 2008, 2018; Mäkinen et al. 2000, 2001, 2002; Jyske et al. 2010; Ge et al. 2010; Ge et al. 2013 a, 2013 b; Hanewinkel et al. 2013; Torssonen et al. 2015).

The current Finnish forest management guidelines for practical forestry (Äijälä et al. 2014) emphasize timber production, particularly sawlog production, as a main goal of management because of its higher economic profitability in terms of NPV (2% interest rate), compared to pulpwood and bioenergy wood. For that purpose, precommercial thinning (tending of seedling stand) is carried out in even-aged forest management once or twice, and it is followed by commercial thinning one to three times before final felling, depending on geographical region, tree species and, site fertility type. Forest management intensity together with environmental conditions (climate and site) affects the growth, carbon sequestration and stocks, and timber production in Finland (see e.g., Thornley and Cannel 2000; Liski et al. 2001; Garcia-Gonzalo et al. 2007 a, b; Routa et al. 2011; Pyörälä et a. 2014; Sievänen et al. 2014).

In Finland, Scots pine, Norway spruce, Silver birch (*Betula pendula* Roth), and Downy birch (*Betula pubescens* Ehrh.) are the most important commercial tree species (Finnish Forest Research Institute 2014). Based on the Finnish management recommendations for practical forestry, it has been suggested to regenerate Norway spruce and Silver birch on upland forests sites of medium fertility with adequate supplies of nutrients and water. Meanwhile, Scots pine is recommended to be regenerated on upland forests on medium and lower fertility and water availability (Äijälä et al. 2014). In spite of this, Norway spruce is still widely regenerated on less fertile sites because of moose and other mammal's damages to young Scots pine and birch stands. The extensive planting of Norway spruce on less fertile sites in southern Finland may reduce the moose and mammal damages. However, it may reduce forest productivity and increase mortality, particularly in southern Finland under the severe climate change (Kellomäki et al. 2008; 2018). This may affect negatively wood supply for both the forest-based bioeconomy and climate change mitigation targets (Ministry of Employment and the Economy; COM/2014/0015 2014).

As a result of increasing mortality, the amount of deadwood available for forest dwelling species most likely would increase under warming climate (Mazziotta et al. 2014). The mean volume of decaying deadwood and other dead trees is currently low in managed forests (i.e., on average < 4 and < 8 m^3 ha^{-1} in the south and north), compared to the natural forests, where it is usually > 40 m^3 ha^{-1} (Siitonen et al. 2001; Finnish Forest Research Institute 2014). In boreal forests, 20-25% of forest-dwelling species (Saproxylic species) are mainly dependent on deadwood of different decay stages and dead trees (Siitonen et al. 2001; Tikkanen et al. 2006; Mökkönen et al. 2011). They require 20-40 m^3 ha^{-1} of deadwood and decaying deadwood (Junninen and Komonen 2011; Müller and Butler 2010). Therefore, maintenance of sufficient amount of deadwood in forests is needed for persistence of deadwood-dependent species.

The development of forest resources and the production of different ecosystem services are strongly affected by prevailing environmental conditions (climate and edaphic factors), current forest structure (age and species composition), the severity of climate change, and the forest management applied (see e.g., Garcia-Gonzalo et al. 2007 a, b; Kellomäki et al. 2008, 2018; Poudel et al. 2012; Hynynen et al. 2015). Sustainable forest management requires a better understanding of possible trade-offs among different ecosystem services. It also requires better understanding on how they are affected by alternative management scenarios under the current and changing climate in different regions and time spans (see e.g., Seidl et al. 2007; Seidl and Lexer 2013; Kindermann et al. 2013; Hynynen et al. 2015; Triviño et al. 2015; Bottalico et al. 2016).

Empirical growth and yield models are widely used to support decision making in practical forest management under the current climate (Hynynen et al. 2015). On the other hand, process-based ecosystem models may be helpful and valuable tools to study the impacts of management on different ecosystem services under the current and changing climate. This would not be possible by employing statistical growth and yield models if assuming no changes in environmental conditions (Kellomäki et al. 2018). So far, most of the previous forest ecosystem model-based impact studies in Finland from the stand to regional level (e.g., Kellomäki et al. 2008; Torssonen et al. 2015; Zubizarreta-Gerendiain et al. 2015) have used climate projections derived from the previous Coupled Model Intercomparison Project 3, CMIP3, or other ones. Few impact studies have used multi-model mean projections (e.g., Ikonen et al. 2017, Kellomäki et al. 2018) or individual GCM projections (Lehtonen et al. 2016 a; Ruosteenoja et al. 2018) of the most recent Coupled Model Intercomparison Project 5, CMIP5 database, under the Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5 forcing scenarios (e.g., Ruosteenoja et al. 2016). Use of different climate change projections is required for a better understanding of the uncertainties related to the projected climate change and its impacts on forests and forestry.

1.2 Uncertainties related to future climate

The use of global climate model (GCM) simulations may help to understand the gradual climate change and its impacts on forests and forestry. The climate model simulation outputs are freely available for researchers from the international data archives. The climate data are available through the Earth System Grid Federation (ESGF), which is an international collaboration that develops, deploys and maintains software infrastructure for the management, dissemination, and analysis the model outputs and observational data. The most recent openly available GCMs were produced under the umbrella of the Coupled Model Intercomparison Project 5, CMIP5. The GCMs are been developed continuously and the model simulations are re-simulated regularly to provide most reliable and updated climate projections.

However, the climate model simulations differ from one model to another and due to greenhouse concentrations used in the simulations. Therefore, and to enhance the robustness and credibility of the projections, an ensemble approach (average and variability among e.g. 28 individual climate models) enhance the value of impact studies. In estimation of the future greenhouse gas concentrations, the Representative Concentration Pathways (RCPs) adopted describe four different radiative forcing pathways (RCPs) of year 2100 (e.g. 2.6, 4.5, 6 and 8.5 W/m^2). More specifically, under the RCP8.5 scenario, emissions continue to increase throughout the 21st century, ultimately nearly three folding and the concentration of CO_2 would approach 1000 ppm by 2100, compared to the current level. In the current CMIP5 GCMs, the horizontal grid size typically varies between 100 and 300 km. This resolution gives rather coarse view on high resolution spatial variation of climate and downscaling of GCM simulation is often needed. As well, GCMs have often systematic biases that have to be corrected prior to use.

Large uncertainties still exist in projections related to climate change. Based on the CMIP5, higher increases in the mean annual temperature are expected and only marginal changes in the mean annual precipitation, compared to the CMIP3 (see Ruosteenoja et al.

2016). In Finland, based on the multi-model mean (RCP4.5 and RCP8.5) projections, the mean temperature during the potential growing season (April-September) is expected to increase by 3-5 C°, and precipitation by 7-11% by 2070-2099, compared to the current climate, depending on greenhouse gas emission scenarios (Ruosteenoja et al. 2016). This corresponds with an increase in atmospheric CO_2 concentration from the current level of 360 ppm to 536 ppm (multi-model mean RCP4.5), and to 807 ppm (multi-model means RCP8.5) during the period 2070-2099. However, at the same time, some individual global climate models (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 in Finland during the potential growing season by 2070–2099. They predict also a slight to moderate increase in precipitation in the north, but only a slight increase (GFDL-CM3 RCP8.5) or decrease (HadGEM2-ES RCP8.5) in precipitation in the south. Thus, individual GCMs may give very different predictions even if they have used the same radiative forcing (e.g. RCP8.5) scenario. This is due to several reasons, e.g. models may differ in terms of model parametrization and structure, and they may use different input datasets, spatial resolution and numerical algorithms, respectively. Depending on predictions by individual GCMs (and RCPs), various adaptive measures may be suggested.

1.3 Aims of the study

This study employed scenario analyses to evaluate the effects of forest management and different CMIP5 climate projections on timber production and carbon stocks of upland boreal forests in Finland. The forest ecosystem model simulations were conducted over a 90-year period from the stand to regional level by using both model stand data (Paper I) and national forest inventory data (10^{th} NFI data, Papers II-III). In simulations it was used data from current climate (period of 1981-2010) and several CMIP5 projections (multi-model means and individual climate model runs) under the RCP4.5 and RCP8.5 forcing scenarios for 2010-2099 (Figure 1). More specifically, the study addressed the following research questions in Papers I-III:

i. How different climate change projections and thinning regimes affect the volume growth, carbon stocks, timber production, and profitability in managed Scots pine, Norway spruce, and Silver birch stands under southern and northern boreal conditions (Paper I)?

ii. How different climate change projections and tree species preferences in forest regeneration affect volume growth, carbon stock and timber production in managed boreal forests throughout Finland (Paper II)?

iii. How different climate change projections and forest management and conservation scenarios affect the volume growth, carbon stock, timber production, and amount of deadwood in boreal forests throughout Finland (Paper III)?

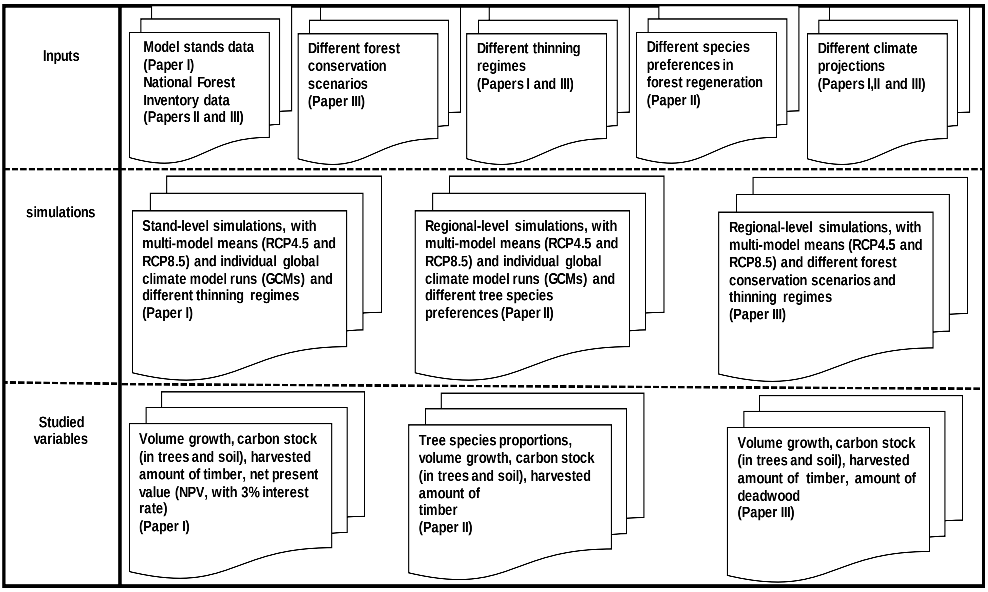

Figure 1 Outline of the study

2 MATERIALS AND METHODS

2.1 Outline of the forest ecosystem model (SIMA) used in the simulations

A gap-type forest ecosystem model (SIMA) (Kellomäki et al. 2005, 2008) was used to simulate the regeneration, growth, and mortality of trees in managed boreal upland forests throughout Finland. The model is capable of simulating the dynamics and development of Finnish boreal upland forests in single-tree species and mixed stands of coniferous and broadleaves species. In the model, the prevailing growing conditions and forest management practices affect the growth and mortality of trees. In the model, the growth of a tree is based on diameter growth, which is affected by the environmental factors (climatic and edaphic factors). The environmental factors are linked to the demographic processes (regeneration, growth and mortality) by different multipliers. The diameter growth of a tree is modelled as a function of the maximum diameter growth, which is affected by the prevailing growing conditions; temperature sum (Tsum, degree days (d.d.) > +5 C°), light conditions, soil moisture and nitrogen supply (multiplier 1 = no reduction and <1 = reduction of diameter growth) (Figure 2). The maximum diameter growth is affected by the diameter of the tree and the atmospheric carbon dioxide (CO_2) concentration. The tree diameter is further used to calculate the height of the tree and mass of different tree organs (foliage, branches, stem, and roots).

The species-specific response to the temperature sum is modeled based on a downwards-opening symmetric parabola (Kienast et al. 1987; Nikolov et al. 1992). The minimum and maximum values of temperature sum define the geographical distribution of each tree species throughout the boreal zone. The minimum, optimum, and maximum temperature sum values for growth are the smallest for Norway spruce (370, 1215, and 2060 d.d.), followed by Scots pine (390, 1445, and 2500 d.d.) and Silver birch (390, 2360, and 4330 d.d.). The effects of temperature increase on growth under different climate change projections are calculated based on the monthly changes in temperature sum compared with the temperature sum of current climate during the potential growing season (April-September).

The soil texture together with field capacity and wilting point define the soil moisture available for growth as a function of precipitation and evaporation. The initial amount of soil organic matter (and carbon) and the nitrogen available for growth are defined based on the site fertility type and regional temperature sum of a current climate (Kellomäki et al. 2005, 2008). The death of the trees is determined by the crowding with the consequent reduction in growth, which determines the risk for a tree to die at a given moment. Litter and dead trees end up on the soil to be decomposed, with the release of nitrogen in the long-run. The amount of soil organic matter (and carbon) and the nitrogen available for growth are also affected by the inputs of litter and deadwood (stem wood, branches, needles and leaves, stumps, and coarse to fine roots) on the soil layer and their decay, where they are decomposed with subsequent release of nitrogen in soil organic matter.

In initializing the simulations at the stand level, the properties of a tree stand are described in terms of tree species with the number of trees per hectare and DBH in each tree cohort. At the regional level, the simulations are carried out utilizing the forest inventory data as an input (10th NFI, of the period 2004-2013). The management control includes artificial regeneration (planting) with the desired spacing and tree species, control of stand density in tending of seedlings stands, thinning, nitrogen fertilization and final cut. In the harvesting, timber (sawlog and pulpwood), and energy wood (branches, tops of the stem, needles, stumps, and coarse to fine roots) can be harvested. The model simulations with a time step of 1 year are 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 run is one realization of all possible time courses of the model. Therefore, each simulation is repeated several times to determine the convergence of the mode, and the mean value only is used in data analysis.

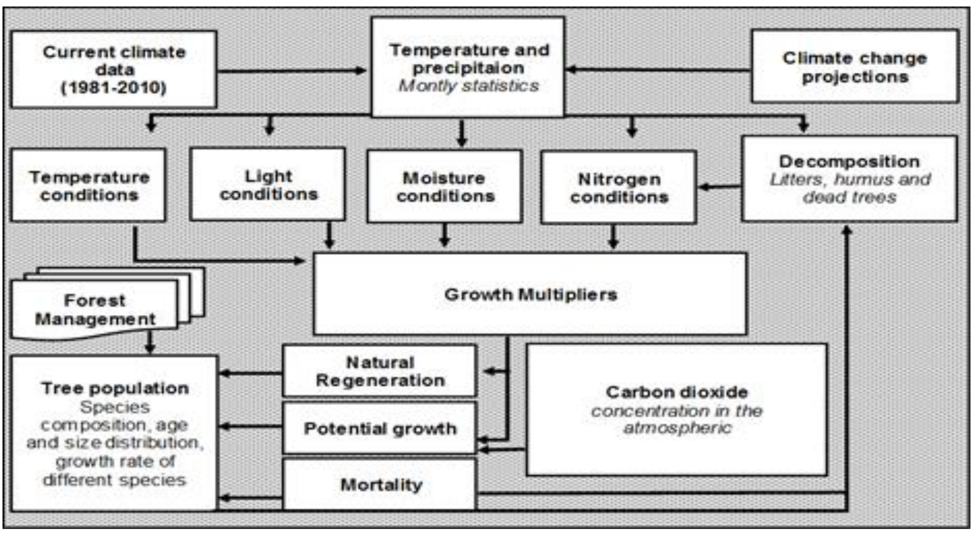

Figure 2 Outline of the forest ecosystem model (SIMA) used in the study

2.2 Model-based simulations and data analyses

2.2.1 Stand-level simulations (Paper I)

In paper I, it was studied the effects of the current climate (CU, period of 1981-2010) and different climate change projections and thinning regimes on volume growth, carbon stocks, (in trees and soil) and amount of harvested timber with its economic profitability based on stand-level simulations (Table 1). The simulations were conducted over a 90-year period using pure stands of Scots pine, Norway spruce, and Silver birch grown on medium fertile sites in southern and northern Finland. In addition to the baseline thinning regime, two alternative thinning regimes were applied (maintenance of 20% higher or lower growing stock in thinning compared to the baseline thinning regime, which follows the current management recommendations). The baseline thinning regime (BT ((0, 0)) implies whenever the basal area threshold for thinning at a given dominant height is reached, the basal area is reduced to the recommended threshold level after thinning (Äijälä et al. 2014). The timing of the final cut was executed at the end of the rotation of the 90-year period. At stand level, using higher growing stock in the thinning (BT (0, 0)), compared to the baseline thinning regimes implies higher timber production and carbon stocks. However, lowering the growing stock in thinnings implies earlier revenue for the forest owners.

For each simulation, volume growth, harvested amount of timber (sawlog and pulpwood), and carbon stocks (in trees and soil) were calculated over the entire 90-year period. The relative effects of climate change were compared in relation to the current climate under the same management regime, and the management effects were compared in relation to the baseline management regime of the same climate projection. Furthermore, the economic profitability of timber production was calculated in terms of net present value (NPV, with 3% interest rate). In this study, the costs of regeneration were excluded from the analyses as these costs were assumed to be same for all simulations. The stumpage prices used for sawlog and pulpwood represented separately the average prices at different thinning and final cut for Scots pine, Norway spruce, and Silver for the whole of Finland (2011-2016).

With respect to climate change, in addition to 10 individual GCM projections, it was used in the simulations multi-model means projections (RCP4.5 and RCP8.5) of two different representative concentration pathways (RCP4.5 and RCP8.5). Out of the 10 individual GCMs, four GCM projections were driven using the representative concentration pathway RCP4.5 and the rest (six GCMs) using RCP8.5. Under the severe individual climate change projection, HadGEM2-ES RCP8.5, the mean temperature during the potential growing season (April-September) is expected to increase by 6.1 °C in the south and north, compared to the current climate (1981-2010). Meanwhile, the precipitation is expected to decrease in the south up to 9%, and in increase up to 7% in the north, compared to the current climate (Table 2).

The current climate data are based on measurements of temperature and precipitation during the reference period (1981-2010). All climate data were obtained from the Finnish Meteorological Institute (FMI), where the data for GCM models were downloaded from the latest CMIP5 database. The interpolation (onto 10 x 10 km grid throughout Finland) for both the current climate and climate change data was done by the approach of Venäläinen et al. (2005) and Aalto et al. (2013), and the bias correction using the monthly correction functions (Lehtonen et al. 2016 a, b; Ruosteenoja et al. 2016). The interpolated and bias-corrected data were used in the SIMA simulations for all climate change projections.

2.2.2 Regional-level simulations (Papers II and III)

In paper II, it was studied the effects of tree species preferences in forest regeneration, and different climate change projections, on tree species proportions, volume growth, harvested amount of timber yield, and carbon stock. The simulations were conducted over a 90-year period at the regional level throughout Finland using the 10th national forest inventory data (same in paper III). The 10th NFI was implemented during the period of 2004-2008 and systematic cluster sampling was applied over the entire country. The distance between clusters varied from 6*6 Km in the most south to 10*10 Km in the most north (Lapland). The shape of clusters also varied depending on geographical region. The angle count sampling (relascope method) was applied to be unbiased on regional level, and it uses non-constant areas of sample plots.

In this study, it was used forest inventory data from one randomly selected sample plot for every permanent cluster of sample plots on upland forests land, in total 2642 sample plots. The simulated values (after one year) of the volume of growing stock were in this study in some degree lower than the measured values for Scots pine and Norway spruce, especially in the south and central forest centres (1-10), based on all sample plots of the 10th NFI. However, the corresponding values were almost the same for birch, regardless of geographical region (Appendix 2).

In addition to the multi-model means projections (RCP4.5 and RCP8.5), it was used in the simulations several individual GCMs. The clear-cut sites on medium fertile sites (1388 plots out of 2642 plots) were planted either by Scots pine, Norway spruce, or Silver birch (Table 1). Moreover, from 10-30% of forest inventory plots from central to northern Finland were randomly left outside of management. However, the plots with higher basal area and/or large trees had higher probability to be selected. For each simulation, tree species proportion (%), volume growth, harvested amount of timber yield, and carbon stock (in trees and soil) were calculated for each 30-year period (2010-2039; 2040-2069 and 2070-2099). The relative effects of changing the tree species preferences in forest regeneration were compared to the baseline management regime. The relative effects of climate change were also compared in relation to the current climate under the same management regime.

In paper III, it was studied the effects of forest conservation scenarios, thinning regimes, and different climate change projections on volume growth, harvested amount of timber yield, carbon stock (in trees and soil), and total amount of deadwood (standing and laying on forest floor) in forests. The simulations were conducted at the regional level using the multi-model means RCP4.5 and RCP8.5 projections over a 90-year period on upland (mineral) soil using 10th National Forest Inventory data (As used II). Site fertility ranged from poor to medium fertile and fertile (67% of total forest area in Finland). In addition to the thinning regimes (same as in paper I), it was used different forest conservation scenarios, i.e., baseline (as in Paper II) and 10% and 20% increases of conservation area, compared to the baseline (Table 1). For each simulation, volume growth, harvested amount of timber yield, carbon stock (in trees and soil), and amount of deadwood were calculated for each 30-year period (2010-2039; 2040-2069 and 2070-2099). The relative effects of forest management and forest conservation scenarios on volume growth, timber yield, carbon stock and dead wood were compared to the baseline management and baseline conservation scenario (BT (0, 0) – BC). However, the relative effects of climate change were compared in relation to the current climate under the same management regime.

Table 1. The inputs and outputs for simulations in Papers I-III over a 90-year period

Parameter	Paper I	Paper II	Paper III
Input			
Tree species (planting density, trees ha^{-1})	Norway spruce and Scots pine spruce (2000), birch (1600)	Norway spruce and Scots pine spruce (2000), birch (1600)	Norway spruce and Scots pine spruce (2000), birch (1600)
Simulation area	Tampere (61° 21' N, 23° 25' E) Rovaniemi (66° 37' N, 25° 38' E)	Whole Finland (60°-70° N, 20°-32°E)	Whole Finland (60°-70° N, 20°-32°E)
Site fertility type	Medium fertile sites	All upland sites	All upland sites
Climate data	Current climate, 10 individual GCMs, and multi-model means RCP4.5 and RCP8.5.	Current climate and multi-model means RCP4.5 and RCP8.5	Current climate, multi-model means (RCP4.5 and RCP8.5)
Nitrogen fertilization	10 Kg ha^{-1}	10 Kg ha^{-}1	10 Kg ha^{-1}
Forest data	Model stand characteristics	10th NFI data	10th NFI data
Final cut timing	End of the rotation (90 years)	Basal area weighted diameter (DBH at 1.3 m, 22-30 cm)	Basal area weighted diameter (DBH at 1.3m, 22-30 cm)
Conservation scenarios	Baseline conservation scenario (BC)	Baseline conservation scenario (BC)	Baseline conservation increased by 10 and 20% (BC+10, BC+20)
Thinning regimes, %	Baseline thinning (BT(0,0)) and ±20%, compared with BT(0,0)	Baseline thinning regime BT(0,0)	Baseline thinning BT(0,0) and ±20% ,compared with BT(0,0)
Change in species preference in forest regeneration	Baseline management regime (same tree species as before final cut)	Scots pine, Norway spruce and Silver birch on medium fertile sites	Baseline management regime (same tree species as before final cut)
Output			
Harvested timber	Sawlogs (≥ 17 cm), pulpwood (6-17 cm)	Sawlogs (≥ 17 cm), pulpwood (6-17 cm)	Sawlogs (≥ 17 cm), pulpwood (6-17 cm)

With regards to the multi-model mean projections (RCP4.5 and RCP8.5), under the RCP4.5 and RCP8.5 scenarios, CO_2 emissions continue to increase throughout the 21st century, approaching 536 and 807 ppm by 2070-2099, compared to the current level. The mean temperature also is expected to increase in Finland by 3-5 °C and precipitation by approximately 7-11% during the potential growing season (April to September) by 2070-2099 (See table 2). 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. They predict also a slight to moderate increase in precipitation in the north, but only a slight increase (GFDL-CM3 RCP8.5) or decrease (HadGEM2-ES RCP8.5) in precipitation in the south. Individual GCMs give very climate predictions even under the same RCPs. Therefore, it is valuable to use climate projections of different GCMs in this study to consider uncertainties related to the projected climate change.

Table 2. Mean changes in temperature (ΔT,°C) and precipitation (ΔP, %) under different CMIP5 projections during potential growing seasons (April–September) during the period 2070–2099 in southern and northern Finland, in comparison to the current climate (1981–2010) (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

3 RESULTS

3.1 Effects of climate change projections and thinning regimes on volume growth, carbon stock, timber production and economic profitability (Paper I, stand level)

In general, the impacts of climate change projections on volume growth, timber production, carbon stocks (in trees and soil), and economic profitability varied largely, depending on tree species, geographical regions and thinning regimes. In northern Finland, the volume growth in Silver birch, Scots pine, and Norway spruce stands increased compared to the current climate, up to 81, 69 and 31%, under different GCMs and thinning regimes. Likewise, timber production and carbon stocks increased in Silver birch, Scots pine, and Norway spruce stands up to 123, 145, and 34%, and up to 23, 16, and 26% respectively, under different GCMs and thinning regimes.

In southern Finland, compared to the current climate, the volume growth in Silver birch stands increased up to 34%, whereas, it decreased in Norway spruce stands, and the most, up to 78%, under different GCMs and thinning regimes. In Scots pine, the volume growth either decreased (up to 11%) or increased (up to 21%) depending on individual GCMs and thinning regimes. In Silver birch and Scots pine stands, timber production either decreased, up to 31 and 59%, or increased, up to 30 and 38%, respectively, depending on individual GCMs and thinning regimes. In Norway spruce stands, the timber could not even be harvested at all under severe climate projections, such as HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5. In Silver birch stands, carbon stock increased, up to 16%, unlike in Norway spruce (decreased up to 60%), under different GCMs and thinning regimes. In Scots pine stands, the carbon stock either increased (up to 10 %) or decreased (up to 16%), depending on individual GCMs and thinning regimes. The moderate climate change, predicted by MPI-ESM-MR RCP4.5, increased volume growth, carbon stocks, and timber production regardless of the geographical region, tree species, and thinning regime (Figure 3).

3.2 Effects of climate change projections and preferences of certain tree species on volume growth, carbon stock and timber production (Paper II, regional level)

In general, the different climate change projections (multi-model means RCP4.5 and RCP8.5, and the individual GCMs) affected volume growth, carbon stocks and timber production more than preferring certain tree species in forest regeneration. However, the preferring certain tree species in forest regeneration affected the development and proportion of tree species more than the climate change projections did. Under the baseline management regime and current climate, volume growth and carbon stock increased from the first to the last 30-year period, regardless of geographical region, unlike timber production.

Under the baseline management regime in northern Finland, the climate change increased volume growth, timber production, and carbon stock, compared to the current climate, up to 102, 160, and 28%, respectively, during the last period 30-year period under GFDL-CM3 RCP8.5 and CNRM-CM5 RCP8.5. In southern Finland, the volume growth, timber production, and carbon stock either increased or decreased depending on climate change projection. For instance, the severe HadGEM2-ES RCP 8.5 projection decreased volume growth, timber production, and carbon stock up to 54, 64, and 35%, respectively, during the last period 30-year period.

Under the current climate, compared to the baseline management regime in southern Finland, volume growth, and carbon stocks of forests increased when either Scots pine, Norway spruce, or Silver birch were preferred. However, preferring Silver birch decreased timber production, unlike preferring Norway spruce. Preferring Scots pine decreased timber production in southern Finland, unlike in northern Finland.

In northern Finland, compared to the baseline management regime and current climate, preferring Scots pine, Norway spruce, and Silver birch increased volume growth, timber production, and carbon stock regardless of climate change projection. For instance, a preferring Silver birch increased volume growth, timber production, and carbon stock, up to 112, 148, and 31%, respectively, under GFDL-CM3 RCP8.5 and CNRM-CM5 RCP8.5) (Figure 4).

In southern Finland, compared to the baseline management regime and current climate, a preferring Norway spruce in forest regeneration decreased volume growth, timber production, and carbon stocks compared to the current climate up to 67, 81, and 47%, respectively, under HadGEM2 ES-RCP 8.5. In contrast, preferring Silver birch increased the corresponding values up to 53, 119, and 9%, and the most under GFDL-CM3 RCP8.5. Preferring of Scots pine either decreased the volume growth, timber production, and carbon stock, up to 57, 62, and 34%, respectively under HadGEM2 ES-RCP 8.5, or increased them up to 29, 15, and 3%, respectively, under the severe GCM projections (CNRM-CM5 RCP8.5) (Figures 4 and 5). Preferring either Silver birch, Scots pine, or Norway spruce in forest regeneration did not affect tree species proportions during the first 30-year period, unlike in the second and last 30-year period. Furthermore, the proportion of Norway spruce decreased even though it was preferred, which was the opposite to Silver birch and Scots pine.

3.3 Effects of climate change projections and forest conservation on the volume growth, carbon stock and total amount of deadwood (Paper III, regional level)

In general, an increase in forest conservation area by 10 or 20% increased volume growth, carbon stock (in trees and soil), and total amount of deadwood more than the maintenance of 20% higher volume of growing stock in thinning regimes, regardless of geographical region and climate applied. However, this was the opposite of the amount of timber production. The maintenance of 20% lower volume of growing stock, compared to the baseline thinning regime, increased the amount of deadwood more than an increase of conservation area regardless of geographical region and climate applied.

Under the current climate and baseline management regime, volume growth, carbon stock, and amount of deadwood increased unlike timber yield, regardless of geographical region. The simultaneous increase in conservation and maintenance of 20% higher growing stock in thinning (BT (+20, +20)-BC+20%), compared to the baseline management regime, further enhanced volume growth, carbon stock, and amount of deadwood up to 14, 38, and 21% regardless of geographical region. However, timber production clearly decreased up to 50% in northern Finland. The maintenance of 20% lower growing stock in thinning regimes did not compensate for the decrease in timber production caused by an increase in the conservation area by 20%, i.e., timber production decreased up to 34% in the north and up to 27% in the south, respectively. Maintenance of 20% lower stocking in thinning and an increase in conservation area by 20% increased the most the amount of deadwood under the current climate. The increase was also the highest, up to 21%, in the north compared with baseline thinning and conservation regimes (Figure 6).

In comparison to the current climate, volume growth, carbon stock, timber production, and amount of deadwood increased under the changing climate, up to 91, 151, 26, and 124%, respectively, depending on geographical region. However, in southern Finland, the multi-model mean RCP8.5 decreased the long-term volume growth, carbon stock and timber production by up to 17-19% compared to the current climate when the growing stock was kept 20% lower than the baseline thinning regime and the conservation area increase by 20% (BT (-20,-20)-BC+20%). The multi-model means (i.e., RCP4.5 and RCP8.5) increased the amount of deadwood up to 146% in northern Finland when the growing stock was kept 20% lower than the baseline thinning regime and the baseline conservation scenario (BT (-20,-20)-BC) was applied (Figure 7).

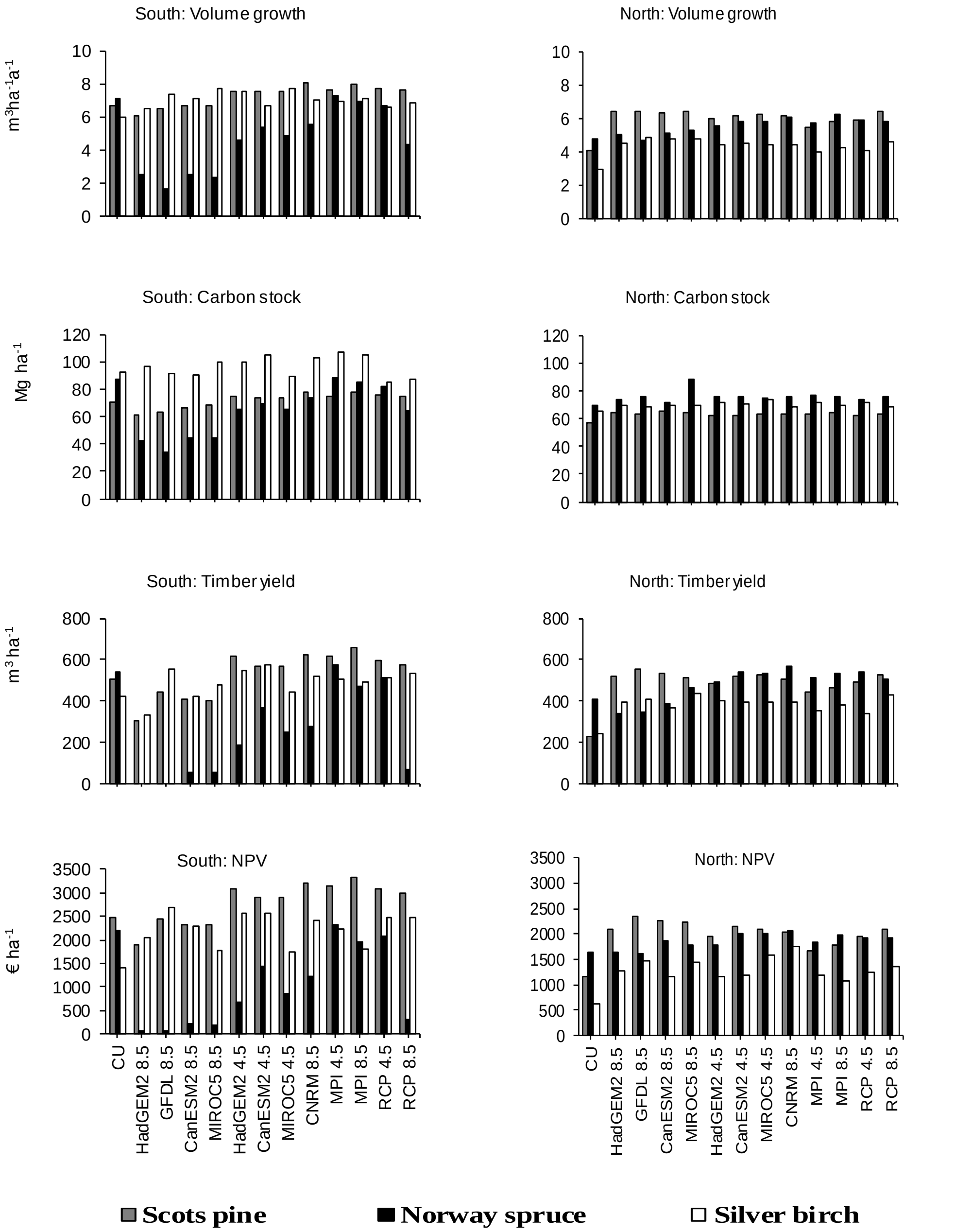

Figure 3 Absolute values of volume growth, carbon stocks, timber yield, and net present value (NPV, with 3% interest rate) in southern and northern Finland for Scots pine, Norway spruce, and Silver birch stands with the baseline thinning regime (BT(0,0)), under the current climate and changing climate projections.

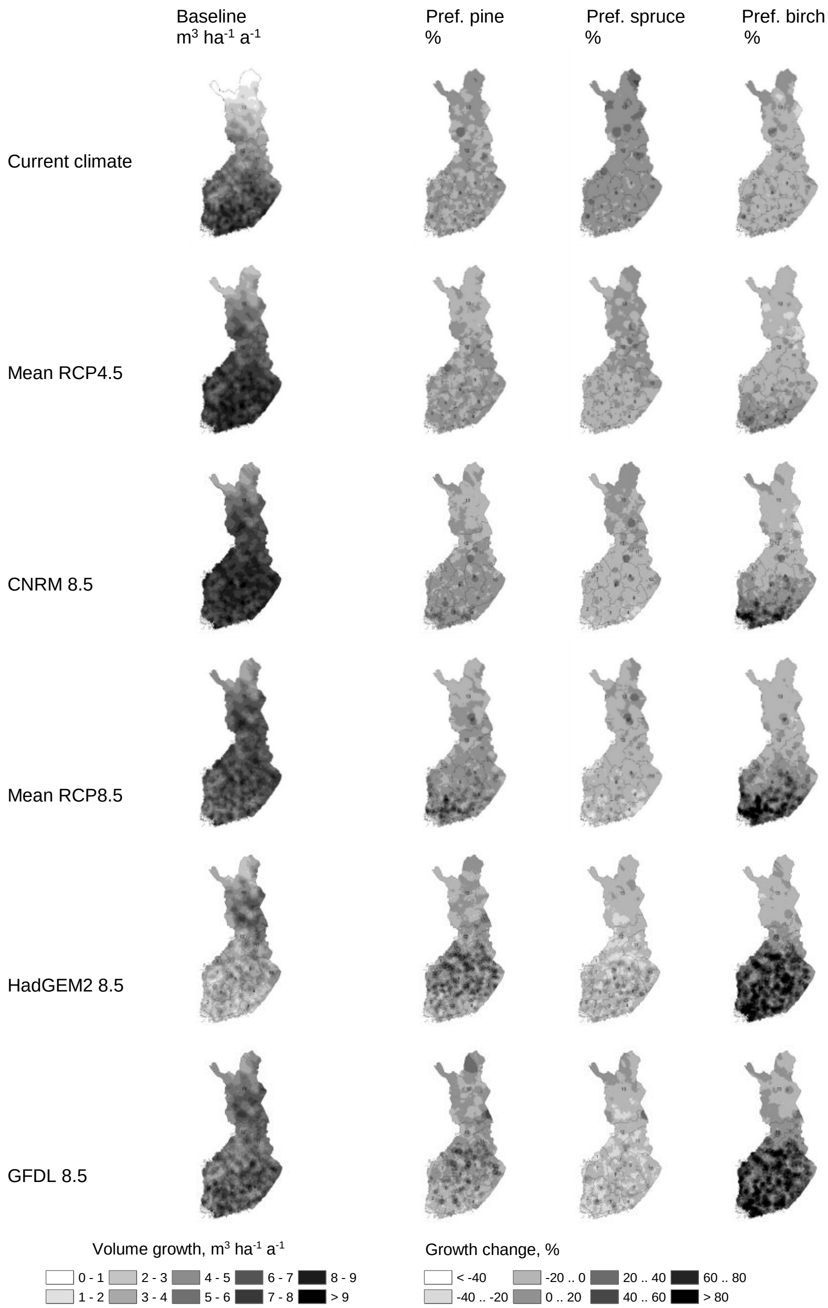

Figure 4 Volume growth ($m^3ha^{-1}a^{-1}$) and its change (%) in different regions of Finland with different management regimes (baseline, pref. for Scots pine, Pref. Norway spruce, and Pref. birch), under the current climate and different climate change projections.

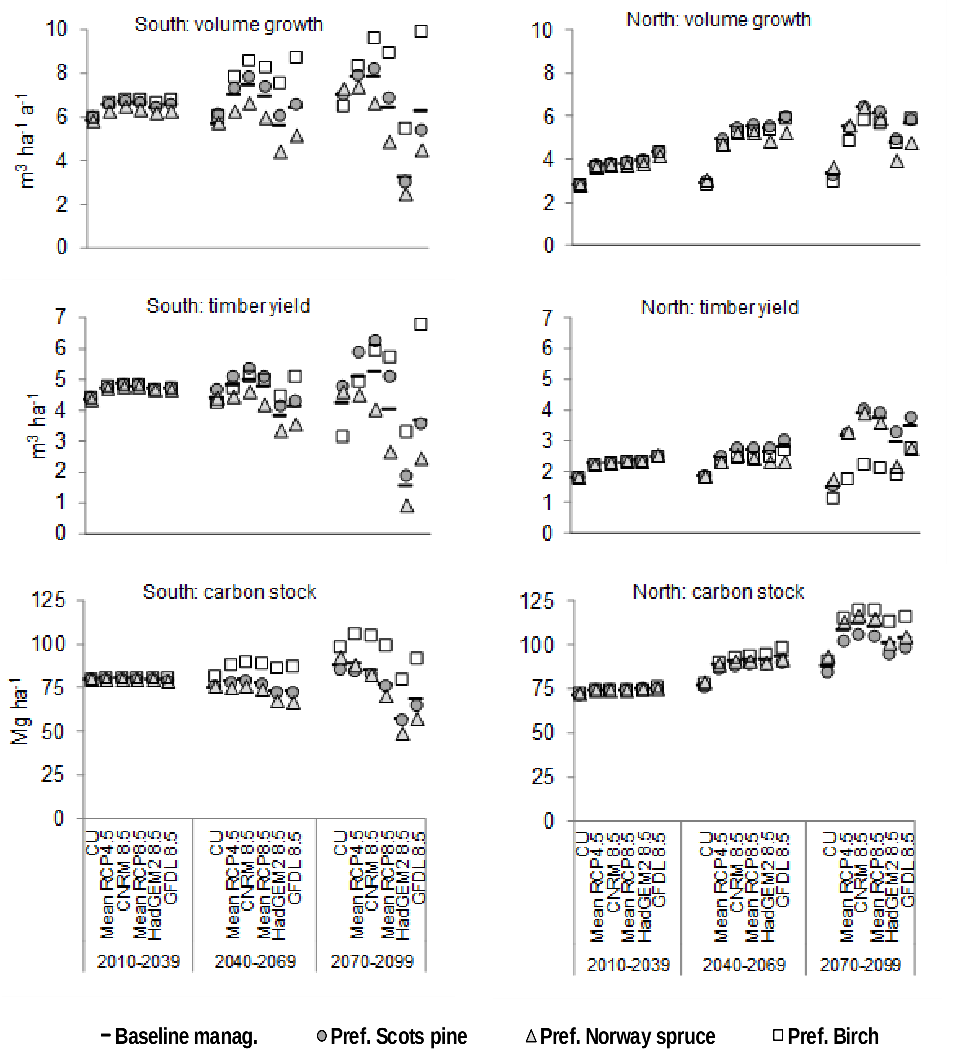

Figure 5 The annual mean stem volume growth (m^3 ha^{-1} a^{-1}), timber yield (m^3 ha^{-1}), and carbon stock (Mg ha^{-1}) in southern and northern Finland with different management regimes, under the current climate and different climate change projections.

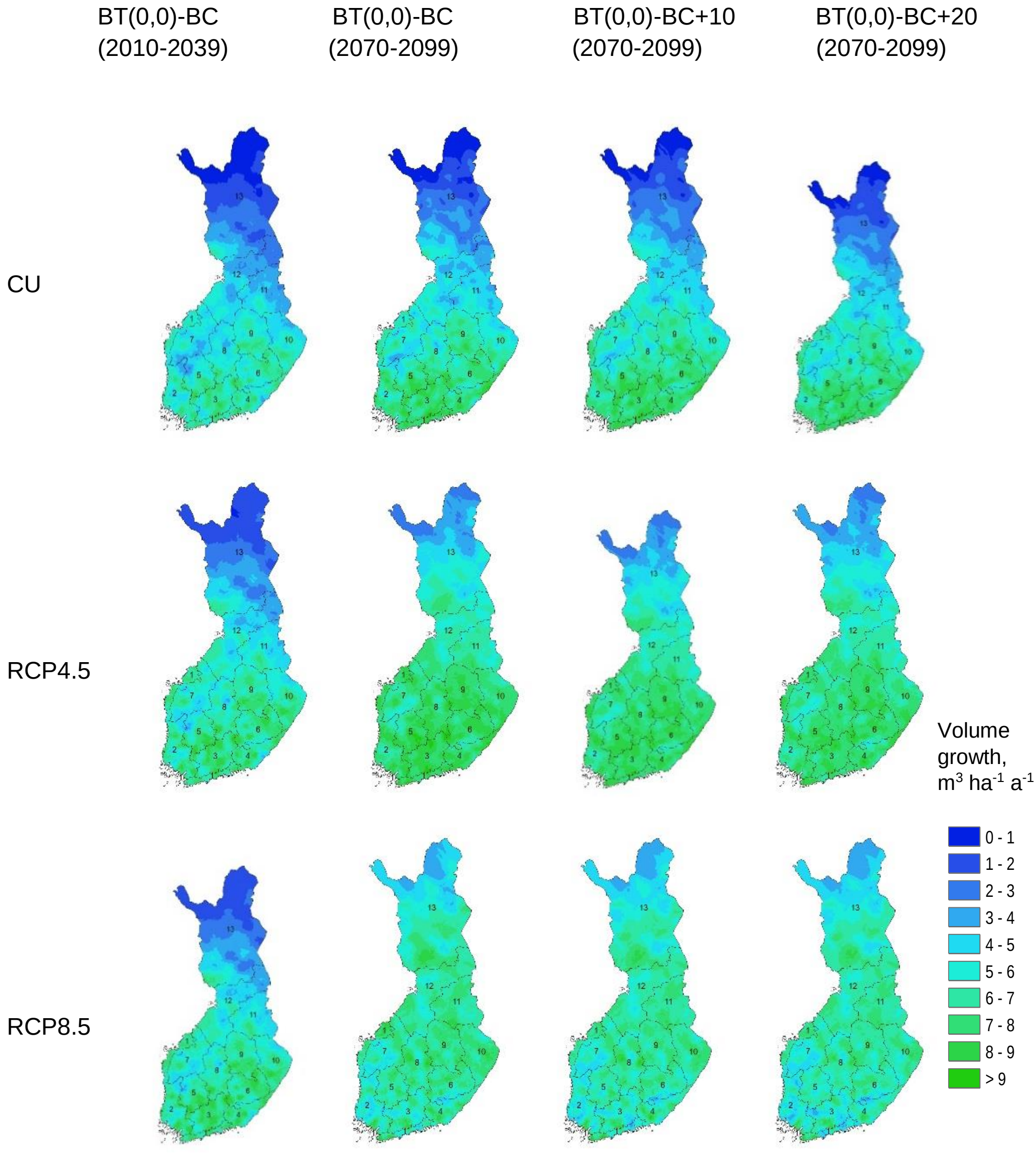

Figure 6 Mean annual volume growth ($m^3ha^{-1}a^{-1}$) in different regions of Finland during the first 30-year period (2010-2039) with the baseline conservation and thinning regime (BT(0, 0)-BC) and last 30-year period (2070-2099) with different conservation scenarios and baseline thinning regime (BT(0,0)-BC, BT(0,0)-BC+10% and BT(0,0)-BC+20%), under the current climate and different climate change projections.

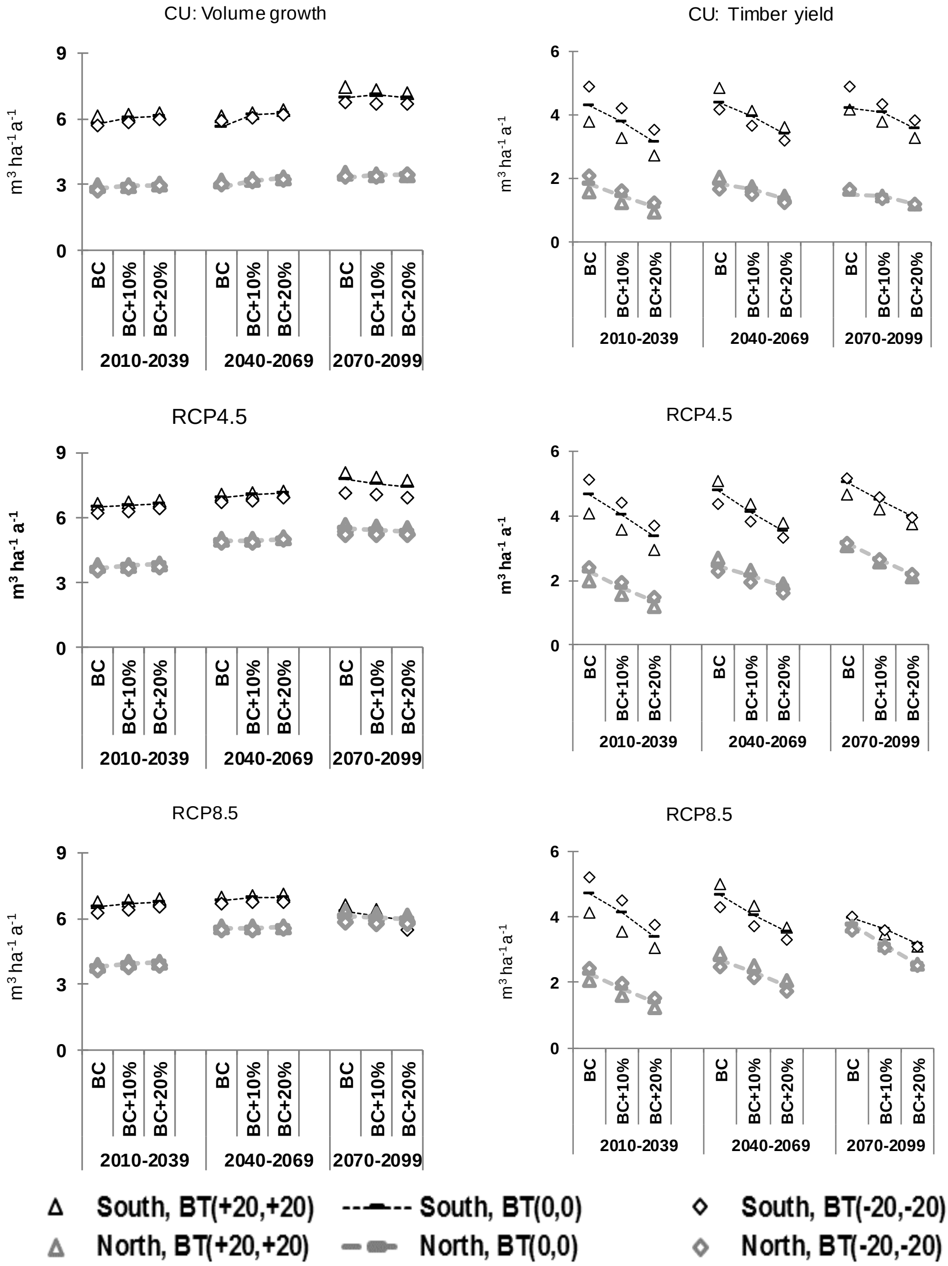

Figure 7 The mean annual volume growth ($m^3ha^{-1}a^{-1}$) and timber yield ($m^3ha^{-1}a^{-1}$) in southern and northern Finland with different forest conservation and thinning regimes, under the current climate and different climate change projections.

4 DISCUSSION AND CONCLUSIONS

4.1 Evaluation of the study approaches

In this work, scenario analyses were used to evaluate the effects of forest management and different CMIP5 climate projections on timber production and carbon stocks of upland boreal forests in Finland using the forest ecosystem model (SIMA), developed by Kellomäki et al. (2005, 2008). The forest ecosystem model simulations were conducted over a 90-year period from the stand to regional level by using both model stand data (Paper I) and 10th national forest inventory data (Papers II-III). In simulations, it was used data from current climate (the period of 1981-2010) and several CMIP5 projections (multi-model means and individual climate model runs) under the RCP4.5 and RCP8.5 forcing scenarios for 2010-2099. Even thought, it was used only the upland boreal forests in this study (covering approximately 67% of total forest area in Finland), the findings may also be applicable, with reservation, to well-drained peatlands with similar site fertility (excluding the carbon in soil).

The forest ecosystem model (SIMA) used in this study is capable of predicting the development of upland forests throughout Finland under the current and changing climatic conditions considering the elevation of temperature and atmospheric CO_2 concentration, and changes in precipitation (see e.g., Kellomäki et al. 2005; 2008). This is not possible using statistical growth and yield models if assuming no changes in current climate conditions (Kellomäki et al. 2018). The model has been parameterized for Scots pine, Norway spruce, silver and downy (*Betula pubescens*) birches growing between the latitudes N 60° and N 70° and longitudes E 20° and E 32° in Finland. The validation of the model by Kellomäki et al. (2008) has shown good agreement between the simulated and measured values of mean annual volume growth of the main Finnish tree species (Scots pine, Norway spruce, and Silver birch) under the current climate on National Forest Inventory plots for different forest regions. The simulation outputs by SIMA model have shown also good correlation with those by the statistical growth and yield model, MOTTI (Hynynen et al. 2002), for mean annual volume growth of managed Norway spruce and Scots pine stands (Routa et al. 2011) under the current climate in different regions of Finland.

The simulated growth responses of different species are sensitive to the minimum, optimum and maximum values of temperature sum, which define the geographical distribution of each tree species throughout the boreal zone. Based on the model simulations, Norway spruce is the most sensitive to the increasing temperature sum, in opposite to silver birch. Based on additional sensitivity analyses shown in appendix 3 (these results not shown in papers I-III), if using in model simulations genotypes which are better adapted also to warmer conditions (i.e. TSmax increase up to 5-10%, see appendix 4), the growth responses of different tree species will change and vary depending on the projected climate change. The growth responses are also controlled by water and nitrogen availability, which are affected by environmental conditions (climate and site, see e.g. Kellomäki et al. 2018). Additionally they are affected by gradual elevation of atmospheric CO_2 (see e.g. Kellomäki et al. 2018).

To consider the uncertainties in climate change, in addition to the current climate, it was used several climate change projections under two different representative concentration pathways (RCP4.5 and RCP8.5), derived from the latest generation of CMIP5, covering the period of 2010-2099. The individual GCMs were selected in this study based on their performance in both simulating the temperature and precipitation under the current and changing climate (see e.g., Lehtonen et al. 2016 a, b; Ruosteenoja et al. 2016, 2017).

The use of multi-model mean changes in projected climate variables, particularly at the daily scale, may result in physically unrealizable changes in climate variables (Madsen et al. 2017). We did not use, however, daily values in our study. The predicted impacts may also vary largely depending on the climate projections applied (Wilcke et al. 2016; Ahlström et al. 2012). Different GCMs do not necessary give same predictions even under the same radiative forcing (e.g. RCP8.5) as was seen in this study, because of differences in model parametrizations and model structure, use of different input datasets, spatial resolution and numerical algorithms. Therefore, to enhance the robustness and credibility of the projections, an ensemble approach (average and variability among different individual climate models) enhance the value of impact studies.

On the other hand, abiotic and biotic damage risks of forests (e.g., insect outbreak and wind-induced damages) were not considered in the simulations, which may, at least partially, counteract the expected increase in forest productivity (see e.g., Subramanian et al. 2016; Reyer et al. 2017; Seidl et al. 2017). In addition, it should be noted that 90-year rotation is quite long especially for silver birch. However, this study used a fixed rotation to simplify the comparison between all tree species. Comparison of results between different rotation lengths would not either reasonable when assuming gradual climate change, unlike under the current climate. Predicting the economic profitability in terms of NPV also involves considerable uncertainties such as volatile timber prices and the interest rate used in the calculations. However, the NPV excludes the value of barren lands, unlike the land expectation value LEV.

4.2 Evaluation of the main findings

4.2.1 Effects of climate change projections on volume growth, carbon stock, timber production and economic profitability

The impacts of different climate change projections on volume growth, carbon stock, timber yield, economic profitability and amount of deadwood varied largely and even were opposite, depending on geographical region, tree species preferences, and severity of climate change projections. In northern Finland, under the baseline management regime, climate change increased the volume growth, carbon stock, timber production (papers I-III), and economic profitability (Paper I), compared to the current climate and regardless of tree species and climate change applied. The largest increases were observed under the severe climate change projections (e.g. GFDL-CM3 RCP8.5 and HadGEM2-ES RCP8.5). Nowadays, the current forest growth in Finland, especially in the north, is restricted by short growing season and low summer temperatures and availability of nutrients (see e.g., Briceño-Elizondo et al. 2006 a, b; Hyvönen et al. 2007; Kellomäki et al. 2008; 2018). Under changing climate, longer and warmer growing season, together with increase in atmospheric CO_2 concentration, may increase the forest growth (see e.g., Saxe et al. 2001; Bergh et al. 2003; Kellomäki et al. 2008; 2018). It may also be increased due to enhanced decomposition of litter and organic matter in soils, which most likely will increase availability of nutrients (see e.g., Saxe et al. 2001; Hyvönen et al. 2007).

In southern Finland, the severe climate change (e.g., GFDL-CM3 RCP8.5 and HadGEM2-ES RCP8.5) decreased volume growth, carbon stock, timber production, with its economic profitability, and the most in Norway spruce stands, but partially also in Scots pine stands (unlike Silver birch stands). The HadGEM2-ES RCP8.5 predicted the highest increase, by 6.1 C°, in mean temperature during the potential growing season in both the south and north by 2070-2099 compared to the current climate. It also predicted a decrease in precipitation in the south, up to 9%, and its increase, up to 7%, in the north. The impacts of individual GCMs, such as GFDL-CM3 RCP8 and CanESM RCP8.5, were higher than those of multi-model means, RCP4.5 and RCP8.5. The large increase in the thermal conditions compared to the current climate (TS> +5 d.d), would turn the current, near-optimal growing conditions for Norway spruce in the south, and partially also for Scots pine, into suboptimal, unlike Silver birch. Earlier, Ruosteenoja et al. (2016) found that under severe increases in greenhouse gas emissions, the number of degree-days (d.d) would increase substantially by the end of 21st century.

It should be noted that even severe climate projections, such as by GFDL-CM3 RCP8.5, showed during April-September higher precipitation in the south and north, by 14 and 26%, respectively, compared to the current climate. However, this did not compensate for the clear reduction in growth caused by simultaneously high increases in temperature, by 6.3 and 7 C° in the south and north, respectively. The reduction in the growth of Norway spruce, and partially Scots pine in the south, may also be increased in the future due to increasing frequency and length of drought events in spring and summer, especially under severe climate change (Ruosteenoja et al. 2018). This finding is in line also with previous experimental studies, which have reported that under warming climate, an increase in drought events may decrease the growth of Norway spruce with its shallow rooting system, especially in southern Finland on forest sites with low water-holding capacity (see e.g., Mäkinen et al. 2000, 2001, 2002; Jyske et al. 2010). Moreover, Henttonen et al. (2015) found that the growth of Scots pine in Finland might also decrease under climate change, even at high northern latitudes. Additionally, in central Europe, especially Norway spruce will most likely suffer especially under changing climate (e.g., Hanewinckel et al. 2013; Schäfer et al. 2017).

4.2.2 Effects of tree species preferences and thinning regimes on volume growth, carbon stock, timber production, and tree species composition

The severity of climate change projection and preferring certain tree species in forest regeneration affected tree species proportion, volume growth, carbon stock, and timber yield in different regions. The increased preference of a certain tree species in forest regeneration (on medium fertile sites) affected the development of tree species proportions more than climate change projections (e.g., multi-model means RCP8.5, HadGEM2 ES-RCP8.5). The degree of the impacts of tree species preferences increased proportionally with an increase in the severity of climate change. For instance, under the severe HadGEM2 ES-RCP8.5 and GFDL-CM3 RCP8.5 projections, the proportion and growth of Norway spruce decreased in line with the severity of climate change, unlike Silver birch. This was mainly because of the differences in species-specific responses to the temperature sum. Likewise, the current forest structure and forest conservation area (increased from southern to northern Finland) affected largely the regional responses of forests to climate change and management regimes. Nowadays, the forests in southern Finland are, in general, younger than in the north and dominated by Norway spruce, whereas in northern Finland, the forests are dominated by Scots pine. The proportion of Norway spruce decreased in this work, even though it was preferred, which was opposite to Silver birch and Scots pine. This is because of the high reduction in the growth of Norway spruce, as caused by the most severe individual GCMs, such as HadGEM2 ES RCP8.5.

This study demonstrated also that preference of Norway spruce in southern Finland decreased volume growth, carbon stock and timber yield and this was most pronounced under severe climate change projections. Therefore, the extensive planting of Norway spruce, particularly in southern Finland on less fertile sites, may decrease carbon sequestration, volume growth, and timber production under severe climate change projections. Furthermore, it may result in large economic losses to forest owners and forestry (Hanewinkel et al. 2013). Additionally, the amount of damages induced by the biotic (e.g. *Heterobasidion* spp. and *Ips typographus*) and abiotic risks (e.g., windstorms and drought), may increase (see e.g., Zeng et al. 2007; Peltola et al. 2010; Reyer et al. 2017; Subramanian et al. 2016; Thom and Seidl et al. 2016; Honkaniemi et al. 2017), especially under the severe warming. On the other hand, Scots pine and birches are more vulnerable to snow-induced damages, compared to Norway spruce (Päätalo et al. 1999; Peltola 1999, 2010; Lehtonen et al. 2016 a). Therefore, the selection of the more heat- and drought-resistant tree species (genotypes), and use of mixtures of conifers and broadleaves forests, could help forests planners to increase timber production, biodiversity and recreational values. This may help to increase the resilience of forests, especially under the severe warming (see e.g., Neuner et al. 2015; Felton et al. 2016; González de Andrés et al. 2016; Pretzsh et al. 2016; Pukkala et al. 2018).

The impacts of thinning regimes, such as by maintenance 20% higher or lower growing stock varied depending on tree species, geographical region, and severity of climate applied. In general, maintenance of 20% higher growing stock in thinning regimes, compared to the baseline thinning regime, enhanced volume growth and increased carbon stock. However, this was opposite to timber yield because of the delay in thinning. Maintenance of 20% higher growing stock in thinning affected the carbon stock more than the climate change projection, unlike the volume growth and timber yield. Maintenance of 20% higher growing stock in thinning might therefore not always be optimal. Based on many previous studies, it has been reported that maintenance of higher growing stock in thinning and use of longer rotation may increase timber production and carbon stock (in trees and soil) at stand level (see e.g., Liski et al. 2001; Briceño-Elizondo et al. 2006 a, b; Garcia-Gonzalo et al. 2007 a, b; Pyörälä et al. 2014; Triviño et al. 2015).

4.2.3 Effects of forest conservation scenarios and thinning regimes on forest volume growth, carbon stock, timber yield, and amount of deadwood

An increase in forest conservation area by 10 or 20% in Finland increased the volume growth, carbon stock (in trees and soil) and amount of deadwood, regardless of climate applied, unlike timber production. From the climate change point of view, increased volume growth, and subsequent carbon sequestration, would provide useful means for mitigation of climate change. Over many decades, Finnish forests have acted as substantial carbon sinks (in trees and soil) (Liski et al. 2006). This is because the annual increment in volume of growing stock has been substantially higher than removals. On average, the annual net removal of carbon dioxide from the atmosphere by Finnish forests is approximately 30 million tons of CO_2, representing 60% of the total emissions for the whole country (Natural Resources Institute 2017). However, it should be considered that higher amount of growing stock, compared to the current, implies more volume stock at risk for different natural disturbances.

On the other hand, a decrease in the amount of harvested timber may also affect the mitigation potential of the forests if less wood-based material would be available for substitution of fossil-based materials and energy. For example, Leppänen et al. (2000) stated that increasing forest conservation areas under the current climate would reduce wood availability for forest industries. On the other hand, based on a studies by Hynynen et al. (2015) and Heinonen et al. (2018), there is potential to increase simultaneously annual removals by applying more intensive forest management, such as increase in forest fertilization and use of improved seedlings stock. From the forest owner point of view, possible compensation of economic losses for increase in forest conservation areas (Mökkönen et al. 2009; Öhman et al. 2011; Triviño et al. 2015) may help to balance the bioeconomy and biodiversity targets at the national level.

Intensive extraction of forest biomass may also have significant consequences on different environmental functions and services (Eyvindson et al. 2018; Pohjanmies et al. 2017). Several studies have indicated trade-offs between intensifying forest biomass harvesting, and maintaining forest biodiversity (Mönkkönen et al. 2014), and recreational values (Verkerk et al. 2014; Eräjää et al. 2010). In addition, Heinonen et al. (2017) found trade-offs between increase in timber removal and amount of deadwood and carbon balance of Finnish forestry during the coming 90 year.

Regardless of region and climate applied, maintenance of 20% lower growing stock, compared to the baseline thinning regime, resulted in this work the highest total amount of deadwood due to increase in logging residues (i.e. coarse roots, branches and stumps), which were left on site. This is also advantage for some deadwood dependent species (Nordén et al. 2004; Selonen et al. 2005; Küffer et al. 2008). The future changes in forest structure (age and tree species) and severity of climate change affect together habitat availability for deadwood-associated species (see e.g., Mazziotta et al. 2016). Therefore, strategies aiming to both enhance forest resilience and integrate simultaneously different ecosystem services are highly needed for sustainable forest management (Repo et al. 2015; Triviño et al. 2017).

4.3 Conclusions

Based on the findings of this work, the impacts of different climate change projections on volume growth, carbon stock, timber yield, economic profitability and amount of deadwood varied largely depending on geographical region, tree species preferences, and severity of climate change projections. The degree of differences in the responses of tree species and boreal regions increased along with the severity of climate change. In simulations, the use of individual GCMs, such as HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5, affected the studied variables more than the use of the multi-model means, RCP4.5 and RCP8.5 projections. The positive impacts of climate change were larger in the north regardless of tree species. In southern Finland, the severe climate change projections, such as those predicted by GDFL-CM3 RCP8.5, most likely would create suboptimal growing conditions for Norway spruce and partially Scots pine, unlike Silver birch. In general, preferring a certain tree species in forest regeneration affected the tree species proportion more than did the climate change projection with the exception of Norway spruce in the south.

The forest productivity and carbon stock are greatly affected by current forest structure (age and species composition), severity of climate change, and forest management. Based on this work, the volume of growing stock will increase in Finland by 2100 even under the current climate (up to 18%), but more under the changing climate (up to 37%), depending on climate change projection) under the baseline management and conservation scenario. This is because the harvested amount of timber was on average about 60% of the total volume growth of growing stock, regardless of climate applied.

In the future, better understanding on how different ecosystem services are affected by alternative forest management strategies and climate change projections is needed for sustainable management and utilization of forest resources (see e.g., Seidl et al. 2007; Kellomäki et al. 2008; Seidl and Lexer 2013; Kindermann et al. 2013). In further studies, it also should be considered increasing risks to forests by various abiotic and biotic forest damages under climate change (see e.g., Reyer et al. 2017). Furthermore, impact studies need to consider also several climate change projections, representing different GCMs and RCPs, respectively, to consider the large uncertainties related to climate change and its impacts on forests and forestry. Evaluation of the economic impacts of climate change and management strategies over a longer period also involves considerable uncertainties, for instance, due to possible changes in timber prices and management costs and the interest rate used in calculations. By considering such uncertainties would be needed in decision making.

An increase in forest conservation area in Finland nowadays may increase the volume growth, carbon stock, and amount of deadwood in forests, unlike timber production. This would imply less forest biomass available for the bioeconomy and subsequently substituting fossil-based materials and energy unless the intensity of forest management is not increased simultaneously on forestland assigned for wood production. Currently, there is pressure to increase forest biomass harvests in the future to meet the increasing wood demands by the forest-based bioeconomy. However, this should be done in a sustainable way by maintaining other ecosystem services. Therefore, management strategies aiming to simultaneously enhance forest resilience and to provide in a sustainable way different ecosystem services are highly needed. For example, favoring mixtures of conifers and broadleaves, and modifying site-specific cultivation of different tree species and thinning practices and using shorter rotation if needed, may help to adapt to climate change in boreal forests and forestry. However, depending on the region, tree species, and severity of climate change, various adaptive measures may be needed to utilize the positive impacts and minimize the harmful impacts of climate change in boreal conditions. By using proper adaptive measures, at least partially it may be counteracted the predicted reduction in forest growth and harmful impacts to different ecosystem services under severe climate change.

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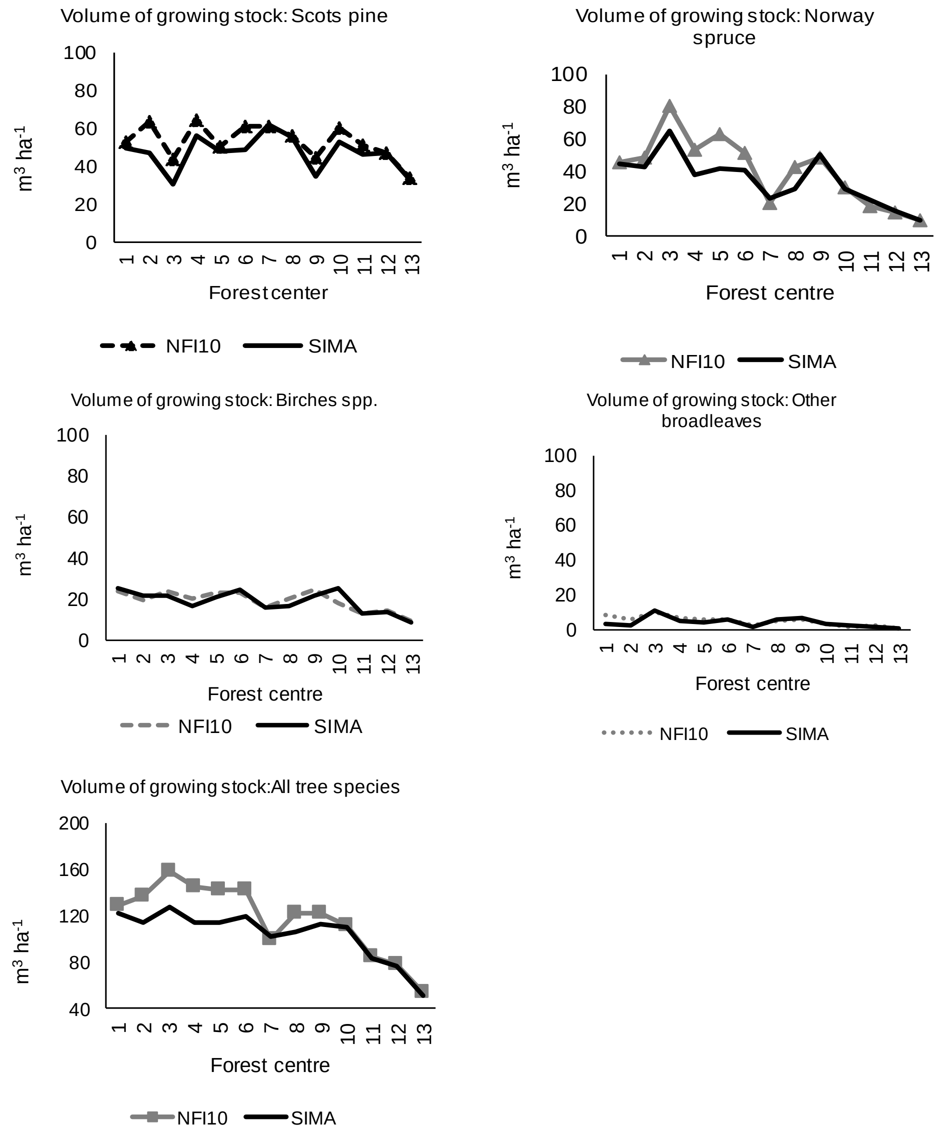
APPENDICES

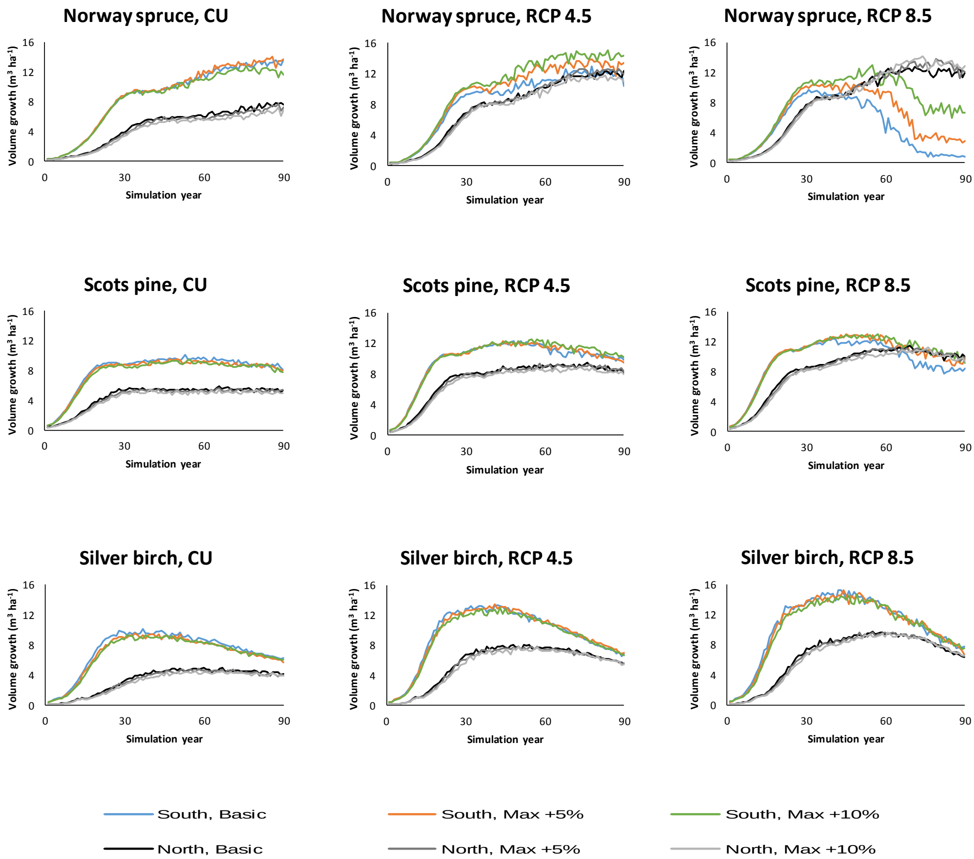
Appendix 1 All 28 individual global climate models (GCMs) used in calculating the multi-model means, under RCP4.5 and RCP8.5 forcing scenarios, in Finland. The first and second columns state the model acronym and the country of origin, and the last Colum a list of variables (T: surface air temperature; PR: precipitation; PSL: sea level pressure; SOL: incident solar radiation at the surface; TXN: difference of the daily maximum and minimum temperatures; W: surface air wind speed) (see more details in Ruosteenoja et al. 2016).

Model	Country	Simulated variables
MIROC5	Japan	T, PR, PSL, SOL, TXN,W
MIROC-ESM	Japan	T, PR, PSL, SOL, TXN,W
MIROC-ESM-CHEM	Japan	T, PR, PSL, SOL, TXN,W
MRI-CGCM3	Japan	T, PR, PSL, SOL, TXN,W
BCC-CSM1-1	China	T, PR, PSL, SOL, TXN,W
INMCM4	Russia	T, PR, PSL, SOL, TXN,W
NorESM1-M	Norway	T, PR, PSL, SOL, TXN
NorESM1-ME	Norway	T, PR, PSL, SOL
HadGEM2-ES	U.K	T, PR, PSL, SOL, TXN,W
HadGEM2-CC	U.K	T, PR, PSL, SOL, TXN,W
MPI-ESM-LR	Germany	T, PR, PSL, SOL, TXN,W
MPI-ESM-MR	Germany	T, PR, PSL, SOL, TXN,W
CNRM-CM5	France	T, PR, PSL, SOL, TXN,W
IPSL-CM5A-LR	France	T, PR, PSL, SOL, W
IPSL-CM5A-MR	France	T, PR, PSL, SOL, W
CMCC-CM	Italy	T, PR, PSL, SOL, TXN,W
CMCC-CMS	Italy	T, PR, PSL, SOL, TXN,W
GFDL-CM3	U.S.A	T, PR, PSL, SOL, TXN,W
GFDL-ESM2M	U.S.A	T, PR, PSL, SOL, TXN,W
GISS-E2-R	U.S.A	T, PR, PSL, SOL, TXN,W
GISS-E2-H	U.S.A	T, PR, PSL, SOL, TXN,W
NCAR-CCSM4	U.S.A	T, PR, PSL, SOL, TXN
NCAR-CESM1-CAM5	U.S.A	T, PR, PSL, SOL, TXN,W
NCAR-CESM1-BGC	U.S.A	T, PR, PSL, SOL, TXN
CanESM2	Canada	T, PR, PSL, SOL, TXN,W
ACCESS1-0	Australia	T, PR, PSL, SOL, TXN,W
ACCESS1-3	Australia	T, PR, PSL, SOL, TXN,W
EC-EARTH	Europe	T, PR, PSL, SOL, TXN,W

Appendix 2 Comparison between the measured values of the volume of growing stock in the 10th NFI and simulated values (after one year simulation) for Scots pine, Norway spruce, birches (Silver and Downy birch), other broadleaves, and as averages of all tree species in different old forest centre areas (south: 1-6; central:7-10 and North:11-13).



Appendix 3 The response of annual and mean volume growth (m^3 ha^{-1}) over 90 years simulation period in Norway spruce, Scots pine and Silver birch to changes in TSmax, compared to basic, on MT sites in southern (S: Tampere) and northern (N: Rovaniemi) Finland. Basic represents the values used model simulations in Papers I-III, and Max +5 and +10 % represent increase of TSmax by 5 and 10%, compared to the Basic values. TSmin was not changed in model simulations, assuming that genotypes with higher TSmax are better adapted both to wider temperature sum range and warmer conditions.



TSmax	Scots pine			Norway spruce			Silver birch		
	CU	RCP4.5	RCP8.5	CU	RCP4.5	RCP8.5	CU	RCP4.5	RCP8.5
S: +5%	3%	0%	6%	2%	10%	31%	-5%	0%	-2%
S: +10%	-5%	2%	8%	-4%	18%	69%	-7%	-3%	-4%
N: +5%	-4%	-2%	-1%	-6%	0%	2%	-5%	-3%	-1%
N: +10%	-8%	-6%	-5%	-12%	-6%	3%	-11%	-6%	-4%

Appendix 4 The tree species-specific response functions to the temperature sum used in sensitivity analyses (results shown in Appendix 3).