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Effects of CMIP5 Projections on Volume Growth, Carbon Stock and Timber Yield in Managed Scots Pine, Norway Spruce and Silver Birch Stands under Southern and Northern Boreal Conditions

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Abstract: We investigated how recent-generation (CMIP5) global climate model projections affect the volume growth, carbon stock, timber yield and its profitability in managed Scots pine, Norway spruce and Silver birch stands on medium fertile upland sites under southern and northern boreal conditions in Finland. Forest ecosystem model simulations were conducted for the current climate and changing climate, under two representative concentration pathways (RCP4.5 and RCP8.5), using 10 individual global climate model (GCM) projections. In addition to the baseline thinning, we maintained either 20% higher or lower stocking in thinning over a 90-year period. In the south, the severe climate projections, such as HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5, as opposed to MPI-ESM-MR RCP4.5, considerably decreased the volume growth, carbon stock and timber yield, as well as its profitability, in Norway spruce stands, but also partially in Scots pine stands, compared to the current climate. Silver birch gained the most from the climate change in the south and Scots pine in the north. The impacts of the thinning regime varied, depending on tree species, site and climate applied. Depending on the severity of the climate change, even opposing adaptive management measures may be needed in different boreal regions.

Keywords: boreal forest; carbon stock; climate change; gap-type forest ecosystem model; forest management; timber yield; volume growth

1. Introduction

Under boreal conditions, Scots pine (*Pinus sylvestris* (L.)), Norway spruce (*Picea abies* (L.). Karst.) and Silver birch (*Betula pendula* Roth.) are economically the most valuable tree species. The growth of boreal tree species is currently restricted by a short growing season, low summer temperatures and a limited supply of nutrients [1,2]. However, forest growth may increase with the changing climate under boreal conditions [1–6]. This is due to potentially longer and warmer growing seasons and an increasing supply of nutrients for growth, as a result of enhanced decomposition of litter and soil organic matter. The projected elevation in atmospheric CO_2 may also enhance forest growth [1,7,8]. The growth responses of different tree species may vary largely, depending on geographical region, site type, severity of climate change and forest management [2,9]. In the southern boreal region, the growing conditions are currently near optimum, especially for Norway spruce, but also partially for Scots pine [2]. Silver birch is expected to gain the most from climate change in the south. In the northern boreal region, growth may increase, regardless of tree species [2].

Based on Finnish forest management recommendations for practical forestry [10], it has been suggested to regenerate Norway spruce and Silver birch from upland medium fertile sites to more fertile sites and Scots pine from medium fertile sites to less fertile sites. Despite this, Norway spruce is nowadays also cultivated on less fertile sites, to reduce browsing damage to forests. This may result in a noticeable reduction in forest growth and timber yield, as well as the economic profitability for forest owners, especially under severe climate change. In the long-term, this may also negatively affect the wood supply for the forest-based bioeconomy [2,9]. Therefore, there may be a need to modify current forest management practices, e.g., site-specific use of tree species, thinning regimes and rotation length, in order to properly adapt to the changing climate [2,11–14]. Even opposing adaptive measures may be needed for different regions and, depending on the targets set for forest management, the severity of the climate change [2,4,12,14].

Large uncertainties still exist in the projected climate change for different regions. Based on the multi-model mean values of 28 recent-generation (Coupled Model Intercomparison Project Phase 5, CMIP5) global climate model (GCM) projections, the mean temperature in Finland during the potential growing season (April–September) may increase by 3–5 °C and mean precipitation by 7–11% under the moderate and severe representative concentration pathway (RCP4.5 and RCP8.5) forcing scenarios, compared to the current climate (1981–2010) [15]. At the same time, the atmospheric CO_2 concentration is expected to increase from the current value of 360 ppm to 536 and 807 ppm during the period 2070–2099 [15]. The multi-model mean values of climate change projections of the CMIP5 database indicate in general a higher increase in temperature, but only marginal changes in the precipitation, compared with the previous CMIP3 database [15]. Some individual GCM projections, such as GFDL-CM3 RCP8.5 (see [15]), predict up to a 6.3 and 7 °C increase in temperature and a 14 and 26% increase in precipitation (April–September) by 2070–2099 in the south and north, respectively; whereas HadGEM2-ES RCP8.5 (see [15]) predicts up to a 6.1 °C increase in temperature, throughout the country. At the same time, HadGEM2-ES RCP8.5 predicts even a 9% decrease in precipitation in the south, as opposed to the north (7% increase).

So far, most of the previous climate change impact studies, either at the stand or regional level, have in Finland been based on the Special Report on Emissions Scenarios (e.g., SRES A1B, CMIP3), or other scenarios [2,16–20]. Only a few recent impact studies have used either some multi-model mean climate projections of the CMIP5 database (e.g., [21,22]) or individual GCM projections as such (e.g., [23,24]), under different RCP forcing scenarios, to consider uncertainties related to climate change and its effects on forests and forestry. However, consideration of such uncertainties is crucial, since the growth responses of forests and consequent adaptive measures may be even opposite depending on the climate change projection used. Forest ecosystem models offer also a means to study the responses of tree species to different forest management measures and climate change projections (see, e.g., [2,17–19,25,26]). Understanding such responses is crucial in order to define sustainable management and utilization strategies of forest resources for changing operative environment, as large trade-offs may occur between the production of different ecosystem services [2,14,21,26–30].

In this work, we investigated for the first time how the individual recent-generation (CMIP5) global climate model projections would affect the volume growth, carbon stock (in trees and soil) and timber yield, as well as its economic profitability in managed Scots pine, Norway spruce and Silver birch stands on medium fertile upland sites under southern and northern boreal conditions in Finland. Gap-type forest ecosystem model (SIMA; see, e.g., [2,31]) simulations were conducted under the current climate (1980–2010) and changing climate, with two representative concentration pathway (RCP4.5 and RCP8.5) forcing scenarios, using altogether 10 individual GCM projections. In addition to baseline thinning, which is currently recommended in practical forestry, we maintained either 20% higher or lower stock in thinning than in the baseline, over a 90-year simulation period.

2. Materials and Methods

2.1. Outline of the Forest Ecosystem Model Used in the Simulations

A gap-type forest ecosystem model (SIMA model; see, e.g., [2,31], Figure 1) was used to simulate the development of managed, pure Scots pine, Norway spruce and Silver birch stands on medium fertile upland forest sites in southern and northern Finland. In the model, the growth and mortality of trees are affected by the prevailing growing conditions and forest management. The diameter growth of a tree is modelled as a function of the maximum diameter growth, which is further scaled in the range from 0–1 to meet the prevailing growing conditions (multiplier 1 = no reduction and <1 = reduction of diameter growth) in relation to the temperature sum (Tsum, degree days (d.d.) >+5 °C), light conditions, soil moisture and nitrogen supply. The maximum diameter growth is also 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 the 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 [32,33]. The minimum and maximum values of temperature sum define the geographical distribution of each tree species through the boreal zone. The minimum, optimum and maximum temperature sum values for growth are the smallest in 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 climate change are calculated based on the changes in monthly temperature sums, compared to the current climate, during the potential growing season (April–September) to meet the prevailing light conditions, as was done in [20].

In the model, the values of the multiplier for light are affected by the height and foliage mass on each tree, the cumulative foliage mass of trees taller than a given tree and the proportion of light above the canopy penetrating through the foliage of taller trees, respectively. The values of the multiplier for soil moisture are affected by the fraction of dry days with inadequate soil moisture for growth in the growing season. The field capacity and wilting point define the available soil water for growth on different soil and site types, as a function of precipitation and evaporation. The values of the multiplier for nitrogen are affected by the nitrogen content of foliage, which is related to the available nitrogen (nitrate and ammonium) in soil for tree growth. Litter from any living organ and the mortality of trees transfer carbon and nitrogen into the soil, where litter and humus (soil organic matter) decay and consequently release nitrogen for tree growth.

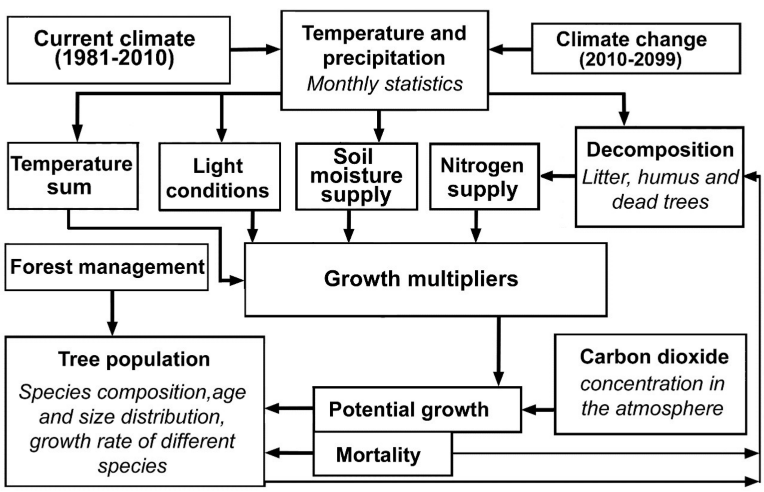

Figure 1. Outlines for the forest ecosystem model SIMA used in the simulations.

To initialize the simulations, the properties of a tree stand are described in terms of tree species, with the number of trees per hectare in each diameter class. The initial amount of soil organic matter (and carbon) and the nitrogen available for growth are based on the site fertility type and regional temperature sum of the current climate [2,31]. In the simulations, management control includes artificial regeneration (planting) with the desired spacing and tree species, control of stand density in thinning and final cut and nitrogen fertilization (see, e.g., [2,20–22,34,35]). In harvesting, in addition to timber (sawlog and pulpwood), energy wood may also be harvested. The model simulations, with a time step of one 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). Each simulation case is repeated many (here 50) times and the mean value of each output variable is used in the data analyses (a minimum of 10–20 iterations are needed to stabilize the mean values).

2.2. Simulations and Data Analyses

The simulations were conducted using pure Scots pine, Norway spruce and Silver birch stands on medium fertile (*Myrtillus*-type) upland sites under southern and northern boreal conditions and current and changing thinning regimes and climates over a 90-year period (Table 1). In the baseline management (thinning) regime, the region-, site- and tree species-specific thinning recommendations for practical forestry were applied. Thus, when a basal area threshold at a given dominant height is reached, the basal area is reduced to the recommended level [10]. In the other two thinning regimes, either 20% higher or lower stock is maintained in the thinnings. The final cut is always done at the end of the 90-year simulation period. Additionally, a long-term mean nitrogen deposition of 10 kg ha^{-1} $year^{-1}$ is used, regardless of the site (see, e.g., [2,31,36]). In addition to the current climate, four individual GCM projections were used in simulations under the RCP4.5 forcing scenarios and six under the RCP8.5 forcing scenarios, respectively (Table 2). They are expected to provide a good representation of the overall variability in the full ensemble of the CMIP5 projections under the RCP4.5 and RCP8.5 forcing scenarios. We used also the multi-model mean monthly values for temperature and precipitation of 28 recent-generation CMIP5 projections under the RCP4.5 and RCP8.5 forcing scenarios in the simulations, as a comparison (these multi-model results are shown mainly in the figures and tables in the Appendix A, but not discussed in detail in the text).

Table 1. Simulation layout with initial site conditions, climates and management activities.

Simulation Layout	Description
Initial site conditions	Medium fertile (*Myrtillus*-type) upland forest sites in southern (Tampere, 61°21′ N, 23°25′ E) and northern Finland (Rovaniemi, 66°37′ N, 25°38′ E). The initial amount of soil organic matter (and carbon) and nitrogen available for growth were defined based on the site fertility type and regional temperature sum of the current climate. A nitrogen deposition of 10 kg $year^{-1}$ was used, regardless of the site.
Climatic conditions	Current climate, altogether 10 individual GCM projections under the RCP4.5 and RCP8.5 forcing scenarios and multi-model mean values for the RCP4.5 and RCP8.5 forcing scenarios.
Forest regeneration	Planting of Norway spruce and Scots pine (2000 seedlings ha^{-1}) and Silver birch (1600 seedlings ha^{-1}), with an initial diameter of 2.5 cm.
Thinning regimes	Baseline management (BT(0,0)) followed the thinning recommendations. In the other management regimes, either a 20% higher (BT(20,20)) or lower (BT(−20,−20)) volume of growing stock was maintained in the thinnings. Thinning was always done from below and at least 10 years before the final felling.
Final cut	A rotation length of 90 years was applied in all simulations.
Harvesting intensity	In thinnings and the final cut, only timber (sawlogs and pulpwood with minimum top diameters of 15 cm and 6 cm) was harvested and the logging residues were left at the sites.

The current climate data are based on measurements of temperature and precipitation taken during the reference period (1981–2010) by the Finnish Meteorological Institute. The data for the GCMs were downloaded from the CMIP5 database by the Finnish Meteorological Institute. The individual GCMs were selected based on their skill at simulating the temperature and precipitation climatology under the current climate (1981–2010) (see, e.g., [23]). However, the predicted values for daily mean temperature and precipitation of individual GCMs (either high or low, in relation to the observed data) were bias-corrected using quantile mapping, which has proven to be among the best-performing empirical bias-correction methods for temperature [37] and precipitation [38] throughout the probability distribution. As a result, the predicted cumulative probability distributions of simulated temperature and precipitation time-series fit properly with the current climate. The interpolation of all climate data onto a 10 × 10 km grid throughout Finland was done by the Finnish Meteorological Institute, using the kriging with external drift (KED) method [39,40].

The mean temperature and precipitation during the potential growing season (April–September) under the current climate was 11.0 °C and 296 mm in southern Finland (old Forest Centre Units 1–6) and 8.3 °C and 286 mm in northern Finland (old Forest Centre Units 10–13). The CO2 concentration was 360 ppm under the current climate (1981–2010). Some individual GCMs, such as HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5, predicted that mean temperature would increase even by 6.1–6.3 °C in the south and by 6.1–7.0 °C in the north by 2070–2099, compared to the current climate (Table 2). At the same time, the mean precipitation would increase by 7–26% in the north, but either decrease by 9% in the south (HadGEM2-ES RCP8.5) or increase by 14% (GFDL-CM3 RCP8.5).

Table 2. Mean changes in temperature (ΔT, °C) and precipitation (ΔP, %) during the potential growing seasons (April–September) in the period 2070–2099 in southern (old Forest Centre Units 1–6) and northern (old Forest Centre Units 10–13) Finland, in comparison to the current climate (1981–2010, with the mean CO_2 concentration of 360 ppm) and the predicted mean atmospheric CO_2 concentration (ppm), under the individual GCM runs. In the table, corresponding values are provided also for the multi-model mean values of 28 GCMs under the RCP4.5 and RCP8.5 forcing scenario (see the country of origin and other info for individual GCMs in [15]].

Global Climate Models (Acronyms)	Short Name	ΔT (°C)		ΔP (%)		CO_2 (ppm)
		South	North	South	North	
HadGEM2-ES RCP8.5	HadGEM2 8.5	6.1	6.1	−9	7	807
GFDL-CM3 RCP8.5	GFDL 8.5	6.3	7	14	26	807
CanESM2 RCP8.5	CanESM2 8.5	5.9	6.3	7	13	807
MIROC5 RCP8.5	MIROC5 8.5	5.6	6	13	15	807
HadGEM2-ES RCP4.5	HadGEM2 4.5	3.5	3.7	2	8	536
CanESM2 RCP4.5	CanESM2 4.5	3.3	3.6	12	13	536
MIROC5 RCP4.5	MIROC5 4.5	3.2	3.3	9	11	536
CNRM-CM5 RCP8.5	CNRM 8.5	3.7	3.9	24	19	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
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

Based on simulations, we analyzed the effects of climate change and thinning regimes on mean annual stem volume growth (m^3 ha^{-1} $year^{-1}$), carbon stock in trees and soil (Mg ha^{-1}) and timber yield (m^3 ha^{-1}) over a 90-year simulation period in Scots pine, Norway spruce and Silver birch stands on medium fertile sites in southern and northern boreal conditions. In addition, we analyzed the net present value (NPV, € ha^{-1}, with a 3% interest rate) of timber yield. The costs for forest regeneration and tending of seedling stands were assumed to be the same, regardless of tree species and region and excluded from the analyses. The unit stumpage prices used for sawlog and pulpwood in different cuttings represented the average values of 2011–2016 of Scots pine, Norway spruce and Silver birch throughout Finland ([41]; see Appendix A, Table A1).

3. Results

3.1. Mean Annual Stem Volume Growth

Under the current climate, with the baseline thinning regime, the mean volume growth over the 90-year period was in the north 2.9, 4.1 and 4.7 m^3 ha^{-1} $year^{-1}$ in Silver birch, Scots pine and Norway spruce stands, respectively. In the south, the corresponding values were 6.0, 6.7 and 7.1 m^3 ha^{-1} $year^{-1}$. Under individual GCMs, the mean volume growth range was in the north 3.9–4.8, 5.4–6.5 and 4.7–6.2 m^3 ha^{-1} $year^{-1}$ for Silver birch, Scots pine and Norway spruce stands, respectively. In the south, their ranges were 6.5–7.7, 6.1–8.1 and 1.6–7.3 m^3 ha^{-1} $year^{-1}$ (Figure 2, Appendix A, Table A2).

Compared to the current climate, the volume growth increased in general in the north by 31–69%, 3–31% and 32–81% in Scots pine, Norway spruce and Silver birch stands, depending on the individual GCM and thinning regime. GFDL-CM3 RCP8.5 was an exception, under which the volume growth decreased in Norway spruce in the north by 3%, compared to the current climate. The volume growth decreased in the south in Norway spruce stands the most, by 78%, under GFDL-CM3 RCP8.5 and the least, by 3%, under MPI-ESM-MR 4.5. Under the most severe climate projections (i.e., GFDL-CM3 RCP8.5 and HadGEM2-ES RCP8.5), the growth started to decline in Norway spruce in the south already after a 30–40-year simulation period. On the other hand, it increased in Norway spruce in the south by 4% under MPI-ESM-MR 4.5. The volume growth increased in Silver birch stands in the south the most, by 34% under GFDL-CM3 RCP8.5 and the least, by 8%, under HadGEM2-ES RCP8.5. In Scots pine stands, the volume growth decreased the most, by 11%, under HadGEM2-ES RCP8.5 and increased the most, by 21% under MPI-ESM-MR RCP8.5.

Under the current climate, the use of 20% higher stocking in thinning increased the volume growth a maximum of 5–7%, compared to the baseline regime, both in the south and north and the most in Silver birch. The use of 20% lower stocking in thinning decreased it the most, by 15% in Silver birch stands in the south. Under the climate change, the use of 20% higher stocking in thinning increased the volume growth the most in Silver birch in the south, by 22% under CanESM2 RCP4.5, opposite the use of 20% lower stocking in thinning (19% decrease) under HadGEM2-ES RCP4.5.

3.2. Total Ecosystem Carbon Stock

Under the current climate, with the baseline thinning regime, the mean carbon stock (in trees and soil) over the 90-year period was in the north 65, 57 and 70 Mg ha^{-1} in Silver birch, Scots pine and Norway spruce stands, respectively. In the south, the corresponding values were 93, 71 and 87 Mg ha^{-1} (Figure 3). Under different GCMs, the mean carbon stock range was in the north 69–74, 62–65 and 72–88 Mg ha^{-1} in Silver birch, Scots pine and Norway spruce stands, respectively. In the south, their ranges were 89–107, 61–78 and 30–88 Mg ha^{-1} (Figure 3, Appendix A, Table A2).

Compared to the current climate, the mean carbon stock remained the same, or increased the maximum in the north by 4–14%, 4–26% and 2–23% in Scots pine, Norway spruce and Silver birch stands, depending on the individual GCM and thinning regime. GFDL-CM3 RCP8.5 was an exception in Norway spruce in the north, under which the volume growth decreased by 5%. The mean carbon stock decreased in the south in Norway spruce stands the most, by 63%, under GFDL-CM3 RCP8.5, but increased by 5% under MPI-ESM-MR RCP4.5. It increased in Silver birch stands in the south the most, by 16% under MPI-ESM-MR RCP4.5, but decreased by 4% under GFDL-CM3 RCP8.5, CanESM2 RCP8.5 and MIROC5 RCP4.5, respectively. In Scots pine, the carbon stock decreased the most, by 16%, under HadGEM2-ES RCP8.5, as opposed to under MPI-ESM-MR RCP8.5.

Under the current climate, the use of 20% higher stocking in thinning increased the mean carbon stock the most in Norway spruce stands in the north, by 14% compared with the baseline regime. The use of 20% lower stocking in thinning decreased the mean carbon stock the most, by 15% in birch stands in the north. However, under the climate change, the use of 20% higher stocking in thinning increased the mean carbon stock the most in Silver birch in the south and north, by 24% under CanESM2 RCP8.5. The use of 20% lower stocking in thinning decreased it the most, at the maximum, by 21% in Silver birch stands in the south under MPI-ESM-MR RCP4.5 and in Norway spruce stands in the north under GFDL-CM3 RCP8.5.

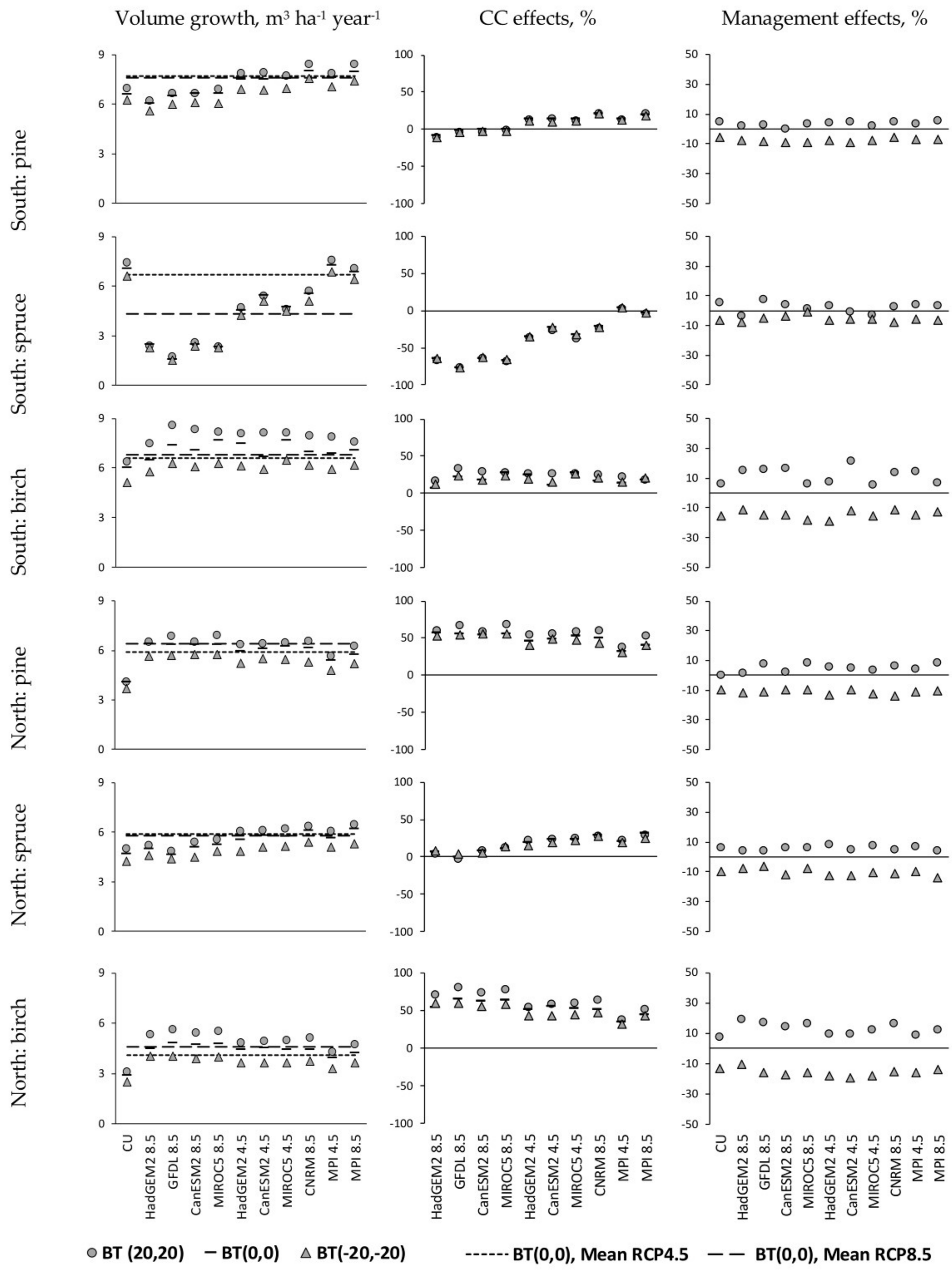

Figure 2. The annual stem volume growth (m^3 ha^{-1} $year^{-1}$) in Scots pine, Norway spruce and Silver birch stands with different management regimes under the current climate (CU, period 1981-2010) and individual climate change, GCMs, projections (shown in table 2), under the RCP4.5 and RCP8.5 forcing scenarios, in southern and northern Finland. As a comparison, absolute values (on the left) for the multi-model means of the GCMs under the RCP4.5 (Mean RCP4.5) and RCP8.5 (Mean RCP8.5) forcing scenarios are shown.

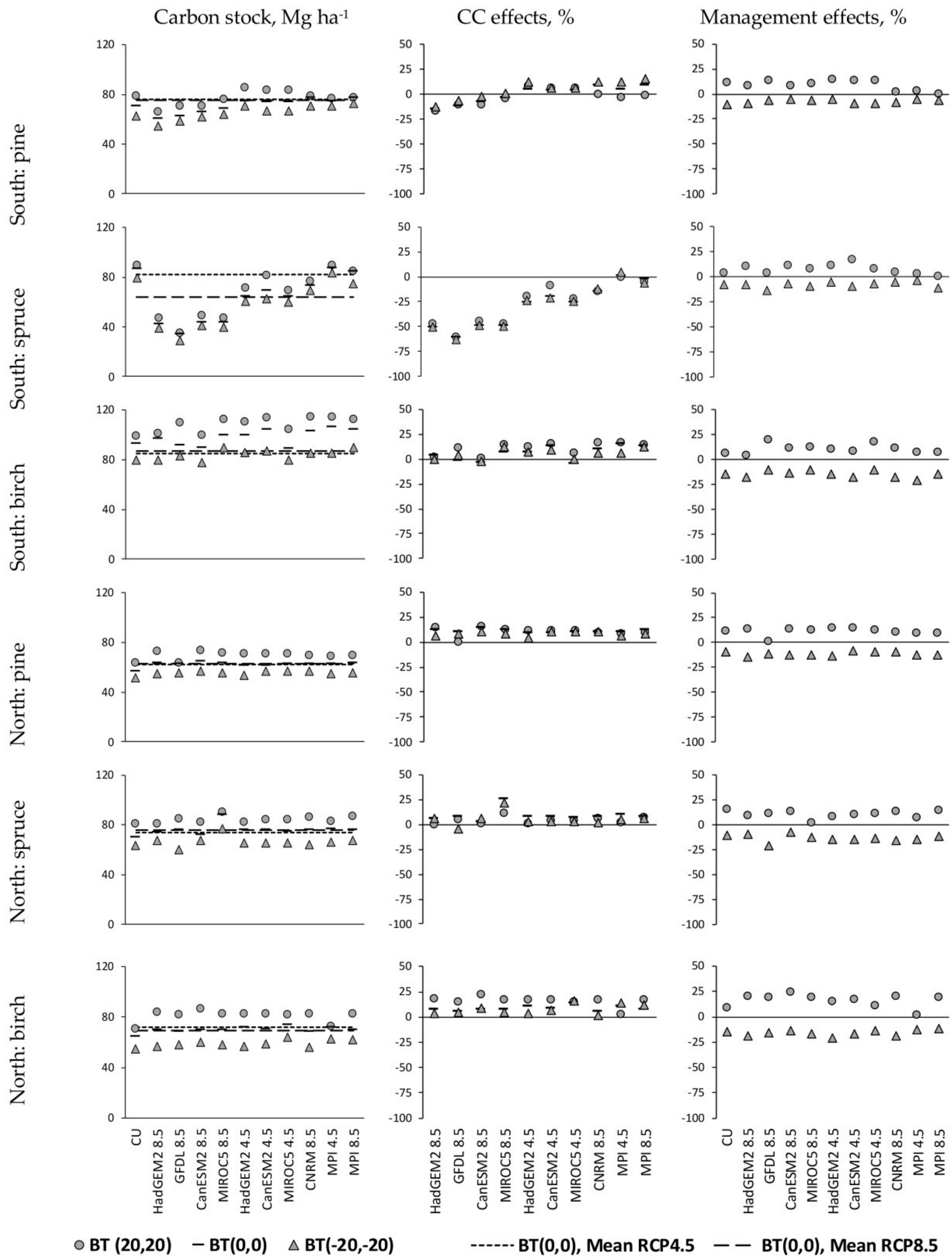

Figure 3. The total ecosystem carbon stock (in trees and soil, Mg ha^{-1}) in Scots pine, Norway spruce and Silver birch stands with different management regimes under the current climate (CU) and individual GCM projections (shown in table 2), under the RCP4.5 and RCP8.5 forcing scenarios, in southern and northern Finland. As a comparison, absolute values (on the left) for the multi-model means of the GCMs under the RCP4.5 (Mean RCP4.5) and RCP8.5 (Mean RCP8.5) forcing scenarios are shown.

3.3. Timber Yield

Under the current climate, with the baseline thinning regime, the timber yield over the 90-year period was in the north 239, 227 and 411 m^3 ha^{-1} in Silver birch, Scots pine and Norway spruce stands, respectively. In the south, the corresponding values were 425, 506 and 541 m^3 ha^{-1}. Under different GCMs, the timber yield range was in the north 349–434, 445–556 and 339–571 m^3 ha^{-1} in Silver birch, Scots pine and Norway spruce stands, respectively. In the south, their ranges were 329–573, 0–575 and 301–657 m^3 ha^{-1} (Figure 4, Appendix A, Table A3). In the north, the timber yield increased in Scots pine and birch stands by 33–145% and 42–123%, compared to the current climate, depending on the GCM and thinning regime. However, in Norway spruce stands, it even decreased, the most, by 35%, under GFDL-CM3 RCP8.5 and increased the most, by 39%, under CNRM-CM5 RCP8.5, compared to the current climate (Figure 4). In the south, the timber yield either decreased in Norway spruce stands considerably or increased only slightly compared to the current climate, regardless of GCM, and it could not even be harvested at all under HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5, respectively. Timber yield increased in Norway spruce stands, the most, by 6%, under MPI-ESM-MR RCP4.5. In Scots pine stands, the timber yield decreased the most, by 59%, in the south under HadGEM2-ES RCP8.5 and increased the most, by 30%, under MPI-ESM-MR RCP8.5. In Silver birch stands, the timber yield increased in the south the most, by 36%, under CanESM2 RCP4.5, but it increased, by 31%, under HadGEM2-ES RCP8.5.

Under the current climate, the use of 20% higher stocking in thinning increased the timber yield the most in Scots pine stands in the north, by 41%, compared with the baseline regime. The use of 20% lower stocking in thinning decreased it in Norway spruce and Silver birch stands in the south and the most, by 10%, in birch stands. In Scots pine stands, it increased the timber yield by 37% in the north. Under the climate change, the use of 20% higher stocking in thinning increased the timber yield the most in Silver birch stands in the north, by 28%, under CanESM2 RCP8.5. The use of 20% lower stocking in thinning decreased the timber yield in the north at maximum by 15–17% in Scots pine under GFDL-CM3 RCP8.5 and in Silver birch under MPI-ESM-MR RCP8.5, MIROC5 RCP 4.5 and CanESM2 RCP4.5, respectively. In the south, the timber yield either increased by 34% under HadGEM2-ES RCP4.5 or decreased by 15% in Norway spruce stands under CanESM2 RCP8.5.

3.4. Economic Profitability of Timber Yield (NPV)

Under the current climate, with the baseline thinning regime, the NPV over the 90-year period was, in Silver birch stands, 622 and 1410 € ha^{-1} in the north and south. In Norway spruce, the corresponding values were 1645 and 2210 € ha^{-1} and in Scots pine stands 1149 and 2473 € ha^{-1}, respectively (Figure 5, Appendix A, Table A3). In the north, the NPV increased the most, in Scots pine stands, by 166% under GFDL-CM3 RCP8.5 and in Silver birch by 264% under MIROC5 RCP8.5, compared to the current climate. In Norway spruce stands, the NPV increased in the north the most, by 68%, under MPI-ESM-MR RCP8.5, and decreased the most, by 19%, under GFDL-CM3 RCP8.5 (Figure 4). In the south, the NPV decreased in Norway spruce stands considerably, especially under HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5 (by up to 100%). In Silver birch stands, it increased the most, by 91%, under GFDL-CM3 RCP8.5. In Scots pine stands, it decreased the most, by 45%, under HadGEM2-ES RCP8.5 and increased the most, by 39%, under MIROC5 RCP4.5 (Figure 5).

Under the current climate, the use of 20% higher stocking in thinning decreased the NPV the most, up to 12%, in Silver birch stands in the north, compared with the baseline regime. The use of 20% lower stocking in thinning increased the NPV in Scots pine and Silver birch stands in the south and the most, up to 17%, in Silver birch stands. However, in Norway spruce stands, it decreased the NPV up to 21% in the north and up to 5% in the south. Under the climate change, the use of 20% higher stocking in thinning increased the NPV the most in Silver birch stands in the north, up to 64%, under CanESM2 RCP8.5. The use of 20% lower stocking in thinning increased the NPV the most in Norway spruce stands in the south, up to 60%, under HadGEM2-ES RCP4.5; whereas it decreased the NPV the most in birch stands in the north, up to 30%, under MPI-ESM-MR RCP4.5.

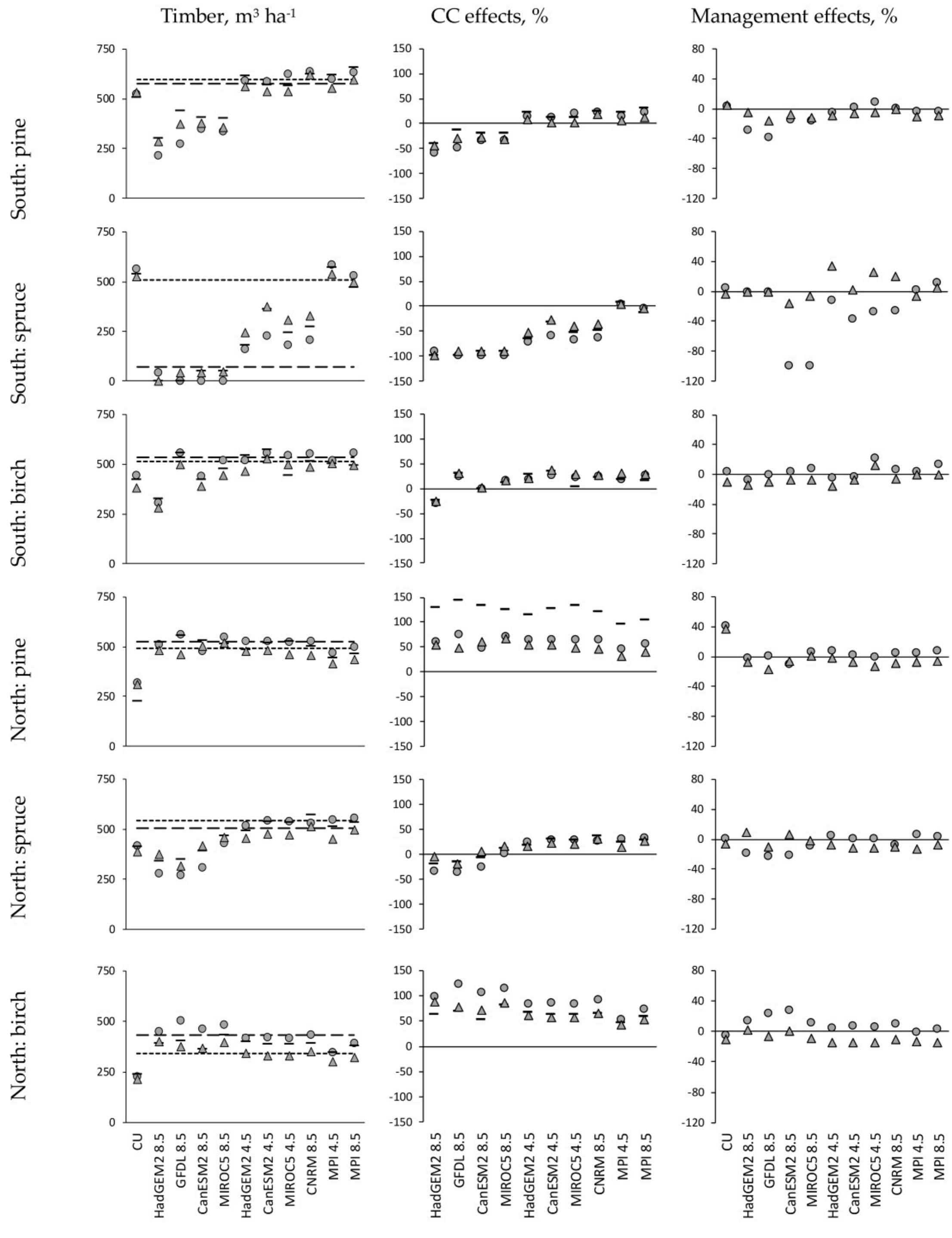

Figure 4. The timber yield (m^3 ha^{-1}) in Scots pine, Norway spruce and Silver birch stands with different management regimes under the current climate (CU) and individual GCM projections (shown in table 2), under the RCP4.5 and RCP8.5 forcing scenarios, in southern and northern Finland. As a comparison, also absolute values (on the left) for the multi-model means of the GCMs under the RCP4.5 (Mean RCP4.5) and RCP8.5 (Mean RCP8.5) forcing scenarios are shown.

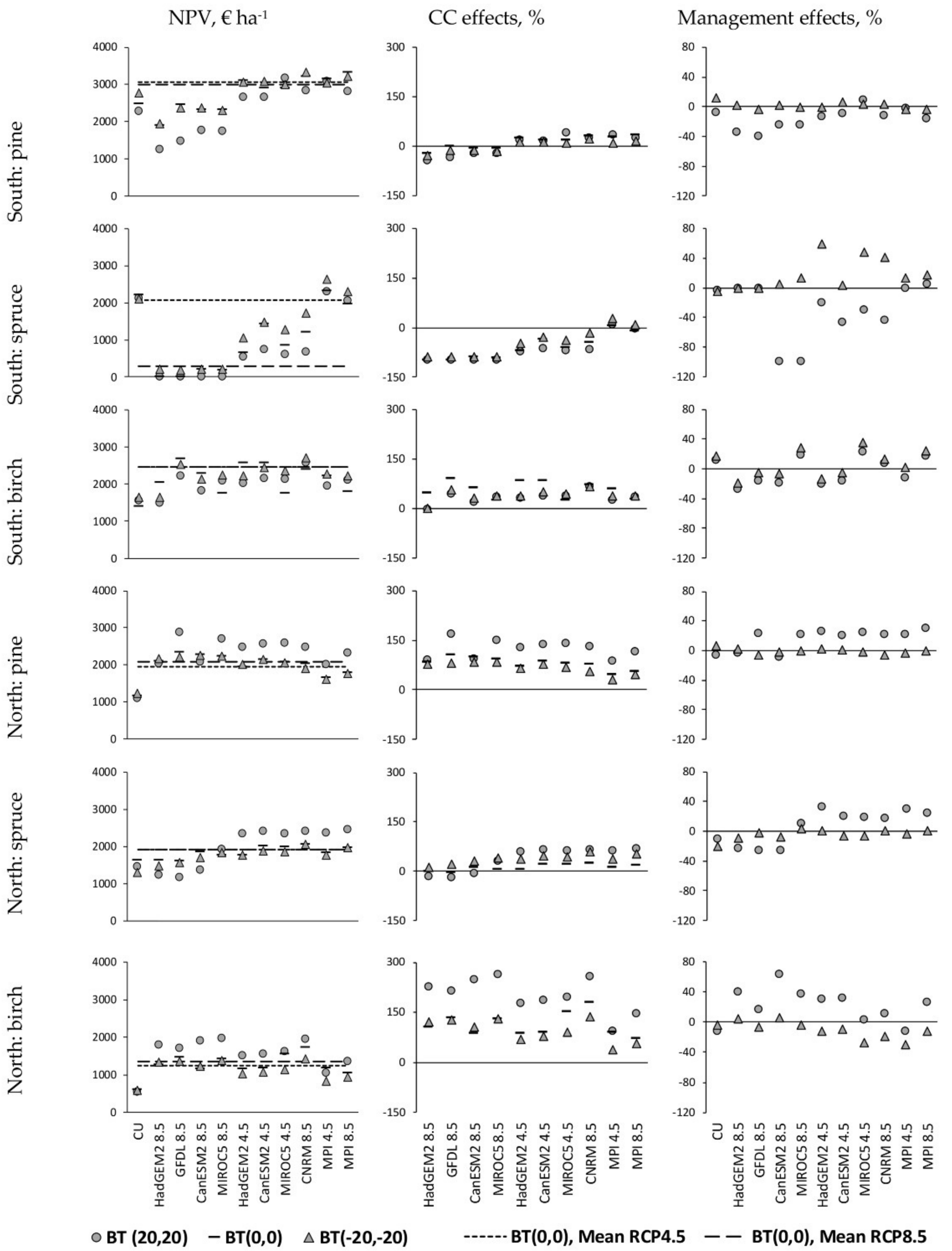

Figure 5. The NPV (€ ha^{-1}) in Scots pine, Norway spruce and birch stands with different management regimes under the current climate (CU) and individual GCM projections (shown in table 2), under the RCP4.5 and RCP8.5 forcing scenarios, in southern and northern Finland. As a comparison, absolute values (on the left) for the multi-model means of the GCM runs under the RCP4.5 (Mean RCP4.5) and RCP8.5 (Mean RCP8.5) forcing scenarios are shown.

4. Discussion

We used in this study a forest ecosystem model (SIMA) to evaluate how recent-generation (CMIP5) global climate model projections affect the volume growth, carbon stock, timber yield and its profitability in managed Scots pine, Norway spruce and Silver birch stands on medium fertile upland sites under southern and northern boreal conditions in Finland. Previous validation for the SIMA model has shown good agreement between the simulated and measured mean annual volume growth of the main boreal tree species (Scots pine, Norway spruce and birch) for old Forest Centre units on National Forest Inventory plots on upland forest sites throughout Finland [2]. Furthermore, the simulated long-term growth responses of trees to the nitrogen fertilization are in good agreement with the measured responses to the nitrogen additions in field conditions [42]. The previous model comparison studies [34] have also indicated a good agreement between simulations by the SIMA model and the empirical growth and yield model (MOTTI model; see, e.g., [43]), for the mean annual volume growth of managed Norway spruce and Scots pine stands on upland medium fertile sites in different locations throughout Finland.

In this study, forest ecosystem model simulations were conducted for the current climate and changing climate, under two representative concentration pathways (RCP4.5 and RCP8.5). The representative set of individual GCMs of the CMIP5 database were selected for this study based on their skill at simulating the temperature and precipitation climatology under the current climate (1981–2010) (see, e.g., [15,23,24,44]). We used in this study also the multi-model mean monthly values for temperature and precipitation of 28 GCMs of CMIP5 database under the RCP4.5 and RCP8.5 forcing scenarios (see, e.g., [21,22]). Some individual GCMs, such as HadGEM2-ES RCP8.5 and GFDL-CM3 RCP8.5, predicted mean temperature increase of 6.1–6.3 °C in the south and 6.1–7.0 °C in the north by 2070–2099, compared to the current climate. At the same time, they predicted a 7–26% increase in mean precipitation in the north, but either a 9% decrease (HadGEM2-ES RCP8.5) or a 14% increase (GFDL-CM3 RCP8.5) in mean precipitation in the south, respectively. As a comparison, the multi-model mean values showed an increase both in mean temperature (up to 3–5 °C) and in mean precipitation (up to 7–11%) under the RCP4.5 and RCP8.5 forcing scenarios [15]. Under the RCP4.5 and RCP8.5 forcing scenarios, the atmospheric CO_2 concentration increased from the current value of 360 ppm to 536 and 807 ppm during the period of 2070–2099, respectively [15].

We used as climate inputs for the simulations mean monthly values for temperature and precipitation for different climate change projections (for individual GCMs and multi-model mean values, respectively) to evaluate the uncertainties related to the projected climate change and its impacts on forest production and carbon sequestration. The use of multi-model mean changes in projected climate variables and especially at a daily scale, may result in physically unrealizable changes in climate variables and consequently affect the interpretation of the results [45]. On the other hand, also the selection of a sub-set of CGMs may affect the interpretation of the results, as well [46,47]. Depending on the CGMs, even opposite impacts may also be predicted, and this may result in costly over-adaptation or mal-adaption of the climate change [48]. Also in our study, the impacts of individual GCM projections on the volume growth, carbon stocks and timber yield and its profitability varied largely and were even opposite for different tree species and boreal regions.

The degree of differences in the responses of tree species increased also along with the severity of climate change projection. This was mainly due to the differences in species-specific responses to the temperature sum. In our study, the minimum and maximum values of temperature sum, which were used to define the geographical distribution of each tree species through the boreal zone, were the smallest in Norway spruce, followed by Scots pine and Silver birch, respectively. Under the most severe climate warming projections, GFDL-CM3 RCP8.5 and HadGEM2-ES RCP8.5, the growth started to decline in Norway spruce in the south already after a 30–40-year simulation period. In addition to the sub-optimal temperature conditions, also insufficient soil moisture supply was expected to limit the growth, especially in Norway spruce in the south. Comparably, based on previous experimental studies, the growth of Norway spruce is expected to suffer under a warming climate, especially on sites with low water-holding capacity [49,50]. In addition, drought episodes might decrease the growth, even in Scots pine, at high northern latitudes [51]. The frequency and duration of drought periods are expected to increase in spring and summer in boreal conditions like elsewhere, especially under severe climate warming [24]. This may make the growing conditions sub-optimal, especially for Norway spruce and partially also for Scots pine, and more optimal for broadleaves (see e.g., [2,4,12,20,52,53]), which need to be considered when adapting management to climate change.

In our study, the longer and warmer growing seasons may also have increased the growth due to increased supply of nutrients for growth, as a result of enhanced decomposition of litter and soil organic matter. The elevation of atmospheric CO_2 enhanced also the growth in our study, as has been found in previous studies (see, e.g., [7,8,22]). However, it could not compensate the effects of the most severe climate warming, which made the growing conditions sub-optimal and thus largely reduced the growth in the south, especially in Norway spruce and partially also in Scots pine.

Severe climate warming projections, such as GFDL-CM3 RCP8.5 and HadGEM2-ES RCP8.5, considerably decreased the volume growth, carbon stock and timber yield, as well as its NPV (with a 3% interest rate) in Norway spruce compared to the current climate as opposed to Silver birch in our study. The range in NPV was highest for the Norway spruce in southern Finland due to drastically decreased volume growth and timber yield under the most severe GCMs. Scots pine stands benefitted the most from the climate change, especially in northern Finland. Under the most severe GCM projections, the growing conditions (especially temperature sum) became sub-optimal, especially for Norway spruce and partly also for Scots pine, especially in southern Finland. This was not observed with the multi-model mean climate projections, in which precipitation increased along with temperature, regardless of the forcing scenario. It is also noteworthy that some individual GCM projections, under the RCP4.5 forcing scenarios, produced reductions similar to those based on the multi-model mean climate projections, under the RCP8.5 forcing scenarios, especially in southern Finland. However, the moderate climate change projection by MPI-ESM-MR RCP4.5 was observed to increase the timber yield and its economic profitability, even in southern Finland, regardless of tree species. Under severe climate change, the growth decreased and mortality increased in Norway spruce, the most under GFDL-CM3 RCP8.5, even though the precipitation during the growing season increases by 14%. In northern Finland, climate change may substantially increase volume growth, timber yield (and its NPV) and carbon stocks (in trees and soil) on upland forest sites under baseline management, compared to the current climate and especially in Silver birch stands (Figure 6). This is because a warming climate makes the thermal growing conditions there more optimal for growth, regardless of tree species [1,2,6,31].

The maintenance of higher stocking in thinning than in the baseline thinning may also increase the volume growth and carbon stock, under the current climate. However, it might not always be optimal under climate change. In fact, the impacts of the thinning regime varied in our study, depending on tree species, site and climate applied. A clear trade-off between the economic profitability of the timber yield and the carbon stock was also observed especially in Norway spruce and partially also in Scots pine stands in the south. It was also observed under the most severe climate change projections in Norway spruce in the north. Predicting economic profitability involves also considerable uncertainties, as volatile timber prices may change over time. In addition, interest rates used in economic calculations can greatly affect the obtained results. The economically optimal rotation length is also affected by the growth rate of different tree species on different sites and geographical regions and the extent of the climate change and associated damage risks to forests.

In our study, the higher growth rate of trees under climate change resulted in earlier thinnings. A fixed rotation length of 90 years was used to simplify the comparison of the results between species, sites and climates. However, the rotation period and thinning intensity may need to be reduced under the climate change. This is due to increasing abiotic and biotic risks to the forests under the climate change [54,55]. Snow damage risks may increase in the north [44] and wind damage risks in the south [54–57]. Scots pine and broadleaves are, in general, more vulnerable to snow damage, whereas Norway spruce is more vulnerable to wind damage [56–59]. Increasing forest damages may partially counteract the expected increase in forest productivity under the changing climate.

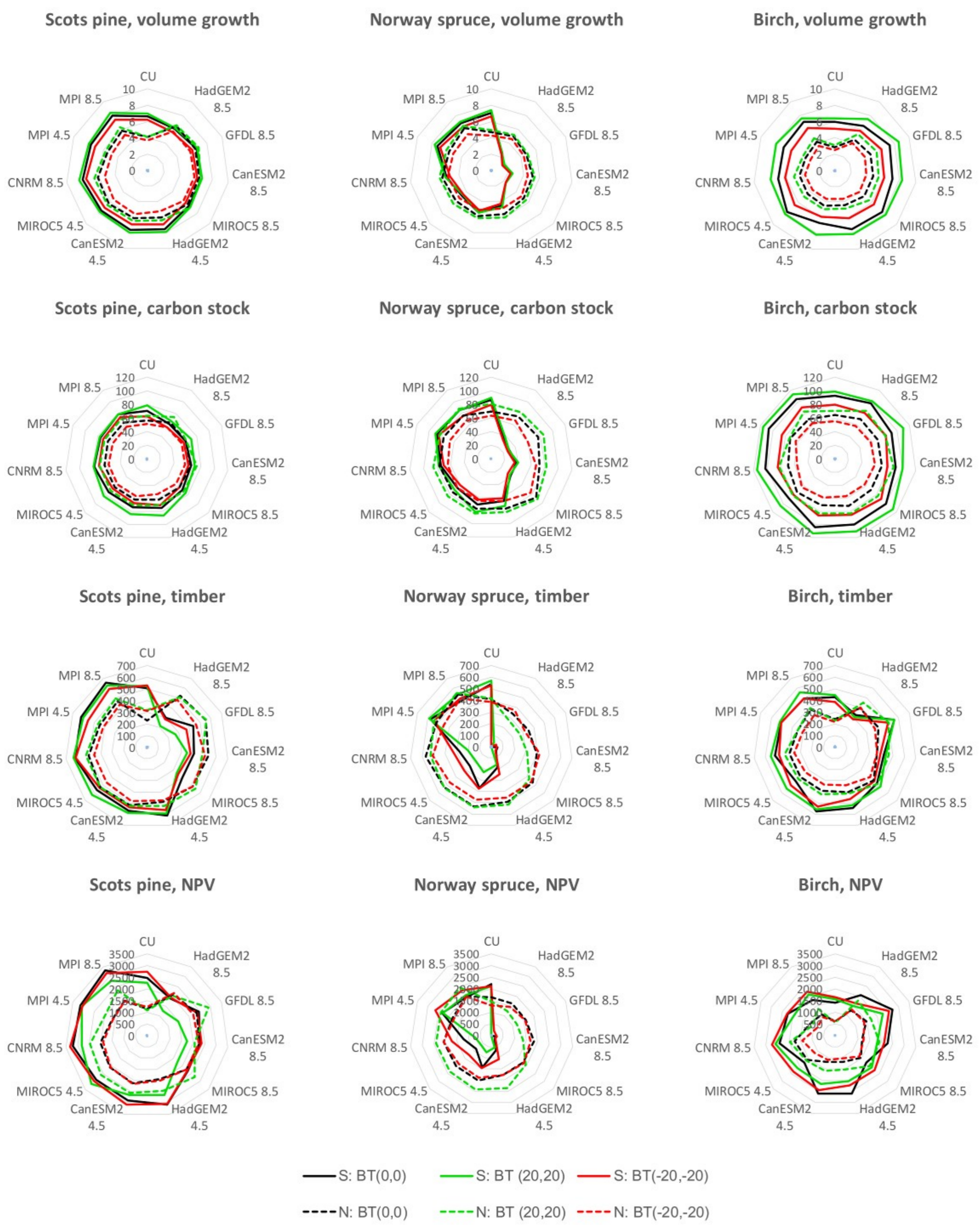

Figure 6. The annual stem volume growth (m^3 ha^{-1} year^{-1}), the total ecosystem carbon stock (Mg ha^{-1}), the timber yield (m^3 ha^{-1}) and the NPV (€ ha^{-1}) of Scots pine, Norway spruce and Silver birch stands with different management regimes under the current climate (CU) and individual GCM projections (shown in table 2), under the RCP4.5 and RCP8.5 forcing scenarios, in southern (S) and northern (N) Finland.

Forest management has until now had a strong focus on conifers in boreal forestry, which may not be the best option under the changing climate. Instead of favoring pure conifers (especially Norway spruce), we should favor especially drought-prone sites, mixtures of conifers (e.g., Scots pine and Norway spruce) and broadleaves, which may increase both the timber yield and biodiversity, as well as recreational values of forests and resilience under warming climate [60–64]. Favoring mixed-species forestry may also make it possible to change in a flexible way the management strategies to respond to the realized climate change in different time spans. On the other hand, forest productivity may also be increased per unit land area by intensifying forest management, e.g., by adopting thinning regimes and rotation length and by using better growing tree species and genotypes (e.g., drought and heat adapted) and forest fertilization, respectively (see e.g., [2,35,65]). This may help to counteract at least partially the expected decrease in forest productivity under the severe climate change and associated increase in various abiotic and biotic risks to forests. However, a big challenge for adaptive forest management and forest managers is how to cope with the observed and predicted climate change impacts and their associated uncertainties [52].

5. Conclusions

Based on our findings, the volume growth, carbon stocks and timber yield, as well as its economic profitability may vary largely in the main boreal tree species stands, depending on the GCM projection and boreal region. The climate projections also clearly affected the results more than the thinning regime did. Overall, there may be a need to modify the current forest management practices gradually, in order to adapt to the changing climate. Different adaptive measures may be needed in different regions and depending on the severity of the climate change and the targets set for forest management, respectively. There is also a crucial need to consider the increasing abiotic and biotic risks to forests and forestry. When studying climate change impacts on forests and forestry, different GCM projections should be considered to provide a better understanding of the uncertainties related to the projected climate change and its impacts on forests and forestry. However, it should be kept in mind that careful selection of the sub-set of CGMs is crucial as it may greatly affect the interpretation of the results and may result in costly and sub-optimal adaption to climate change.

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Author Contributions: Heli Peltola and Laith ALRahahleh designed the study. Harri Strandman introduced the climate change datasets into the SIMA model and ran the simulations. Laith ALRahahleh simulated and analyzed the data. Veli-pekka Ikonen finalized all figures in co-operation with Laith ALRahahleh and Antti Kilpeläinen. Laith ALRahahleh had the main responsibility of writing the paper. Veli-Pekka Ikonen, Antti Kilpeläinen, Heli Peltola and Ari Venäläinen participated in writing the manuscript by commenting and editing it.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Stumpage prices for different tree species (Scots pine, Norway spruce and birch), cutting types and timber assortments (2011–2016) over the whole of Finland. No sawlogs were harvested in the first thinning.

Timber Assortment	Tree Species	Unit Stumpage Prices (€ m^{-3})		
		1st Thinning	Other Thinnings	Final Cut
Pulpwood	Scots pine	12	15	18
	Norway spruce	12	16	19
	Silver birch	12	14	17
Sawlog	Scots pine	40	48	56
	Norway spruce	40	48	56
	Silver birch	33	37	43

Table A2. Mean annual volume growth (m^3 ha^{-1} $year^{-1}$) and total ecosystem carbon stock (Mg ha^{-1}) over a 90-year simulation period in Scots pine, Norway spruce and birch stands on medium fertile sites in southern and northern Finland under the current climate (CU) and different climate change projections and management scenarios. S = south, N = north.

Climate	Volume growth, m^3 ha^{-1} $year^{-1}$						Carbon stock, Mg ha^{-1}					
	BT(0,0)		BT(20,20)		BT(−20,−20)		BT(0,0)		BT(20,20)		BT(−20,−20)	
Scots pine	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**
CU	6.7	4.1	7.0	4.1	6.3	3.7	71	57	79	64	63	52
HadGEM2 8.5	6.1	6.5	6.2	6.6	5.6	5.7	61	64	66	73	55	55
GFDL 8.5	6.5	6.4	6.7	6.9	6.0	5.7	63	63	71	64	59	56
CanESM2 8.5	6.7	6.4	6.7	6.5	6.1	5.8	66	65	71	74	62	57
MIROC5 8.5	6.7	6.4	6.9	6.9	6.1	5.8	69	64	76	72	64	56
HadGEM2 4.5	7.6	6.0	7.9	6.4	6.9	5.2	75	62	86	71	71	54
CanESM2 4.5	7.6	6.1	7.9	6.4	6.9	5.5	74	62	84	71	67	57
MIROC5 4.5	7.6	6.3	7.7	6.5	7.0	5.5	74	63	84	71	67	57
CNRM 8.5	8.1	6.2	8.4	6.6	7.6	5.3	78	63	79	70	71	57
MPI 4.5	7.6	5.4	7.9	5.7	7.1	4.8	75	63	77	69	71	55
MPI 8.5	8.0	5.8	8.4	6.3	7.4	5.2	78	64	78	70	73	56
Mean RCP4.5	7.7	5.9	8.1	6.1	7.2	5.3	76	62	86	68	70	55
Mean RCP8.5	7.6	6.4	8.1	6.8	7.1	5.7	75	63	85	72	67	59
Norway spruce	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**
CU	7.1	4.7	7.4	5	6.6	4.3	87	70	90	81	80	63
HadGEM2 8.5	2.5	5.0	2.4	5.2	2.3	4.6	43	74	47	81	39	67
GFDL 8.5	1.6	4.7	1.7	4.9	1.5	4.4	34	76	36	85	30	60
CanESM2 8.5	2.5	5.1	2.6	5.4	2.4	4.5	44	72	49	82	41	67
MIROC5 8.5	2.3	5.2	2.3	5.6	2.3	4.9	44	88	47	90	40	77
HadGEM2 4.5	4.6	5.6	4.7	6.1	4.3	4.9	65	76	72	82	61	65
CanESM2 4.5	5.4	5.8	5.4	6.1	5.1	5.1	70	76	82	84	63	65
MIROC5 4.5	4.8	5.8	4.6	6.2	4.5	5.2	65	75	70	84	60	65
CNRM 8.5	5.5	6.1	5.7	6.4	5.1	5.4	74	76	77	86	70	64
MPI 4.5	7.3	5.7	7.6	6.1	6.9	5.1	88	77	90	83	84	66
MPI 8.5	6.9	6.2	7.1	6.5	6.4	5.3	85	76	85	87	75	67
Mean RCP4.5	6.7	5.9	6.8	6.1	6.1	5.1	82	74	84	84	65	66
Mean RCP8.5	4.3	5.8	4.6	6.3	4.3	5.2	64	76	69	86	59	66
Silver birch	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**
CU	6.0	2.9	6.4	3.1	5.1	2.5	93	65	99	71	80	55
HadGEM2 8.5	6.5	4.5	7.5	5.3	5.8	4.0	97	70	101	84	80	57
GFDL 8.5	7.4	4.8	8.6	5.6	6.3	4.0	92	69	110	82	83	58
CanESM2 8.5	7.1	4.7	8.3	5.4	6.1	3.9	90	70	100	87	78	60
MIROC5 8.5	7.7	4.8	8.2	5.5	6.3	4.0	100	70	113	83	90	58
HadGEM2 4.5	7.5	4.4	8.1	4.8	6.1	3.6	100	72	111	83	86	57
CanESM2 4.5	6.7	4.5	8.2	4.9	5.9	3.6	105	71	114	83	87	59
MIROC5 4.5	7.7	4.4	8.1	4.9	6.5	3.6	89	74	105	82	80	64
CNRM 8.5	7.0	4.4	8.0	5.1	6.2	3.7	103	69	115	83	85	56
MPI 4.5	6.9	3.9	7.9	4.3	5.9	3.3	107	72	115	73	85	63
MPI 8.5	7.1	4.2	7.6	4.7	6.2	3.6	105	70	113	83	90	62
Mean RCP4.5	6.6	4.1	7.7	4.6	5.9	3.3	85	72	110	81	79	59
Mean RCP8.5	6.8	4.6	8.3	5.3	6.0	3.9	87	69	110	82	80	56

Table A3. Timber yield (m^3 ha^{-1}) and its NPV (€ ha^{-1}) over a 90-year simulation period in Scots pine, Norway spruce and birch stands on medium fertile sites in southern and northern Finland under the current climate (CU) and different climate change projections and management scenarios. S = south, N = north.

Climate	Timber Yield, m^3 ha^{-1}						NPV, € ha^{-1}					
	BT(0,0)		BT(20,20)		BT(−20,−20)		BT(0,0)		BT(20,20)		BT(−20,−20)	
Scots pine	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**	**S**	**N**
CU	506	227	523	319	530	311	2473	1149	2273	1082	2750	1226
HadGEM2 8.5	301	522	214	512	285	482	1897	2090	1245	2033	1925	2155
GFDL 8.5	440	556	270	563	371	462	2454	2339	1474	2883	2365	2195

Table A3. *Cont.*

Climate	Timber Yield, m^3 ha^{-1}						NPV, € ha^{-1}					
	BT(0,0)		BT(20,20)		BT(−20,−20)		BT(0,0)		BT(20,20)		BT(−20,−20)	
Scots pine	S	N	S	N	S	N	S	N	S	N	S	N
CanESM2 8.5	406	532	346	477	376	501	2317	2268	1750	2067	2366	2246
MIROC5 8.5	402	514	337	548	355	519	2319	2221	1733	2701	2292	2224
HadGEM2 4.5	614	487	590	527	563	478	3088	1946	2655	2466	3040	1998
CanESM2 4.5	568	518	584	528	536	480	2906	2137	2644	2567	3048	2147
MIROC5 4.5	566	530	623	526	537	461	2890	2080	3165	2594	2984	2059
CNRM 8.5	624	504	634	526	621	456	3206	2027	2836	2474	3317	1897
MPI 4.5	619	445	599	468	555	413	3146	1653	3075	2009	3030	1599
MPI 8.5	657	465	632	498	596	436	3322	1775	2797	2310	3201	1768
Mean RCP4.5	598	492	623	485	583	460	3073	1949	2769	2270	3132	1940
Mean RCP8.5	574	524	561	544	545	477	2985	2082	2529	2587	3056	2067
Norway spruce	S	N	S	N	S	N	S	N	S	N	S	N
CU	541	411	567	413	527	387	2210	1645	2121	1460	2102	1294
HadGEM2 8.5	0	339	45	275	0	371	0	1640	0	1242	220	1474
GFDL 8.5	0	349	0	268	43	314	0	1615	0	1178	192	1577
CanESM2 8.5	53	390	0	307	45	416	212	1855	0	1375	222	1697
MIROC5 8.5	51	466	0	427	48	455	196	1771	0	1935	222	1830
HadGEM2 4.5	182	492	161	516	244	453	667	1773	536	2347	1064	1781
CanESM2 4.5	366	538	230	539	375	476	1427	2019	754	2419	1475	1893
MIROC5 4.5	247	534	182	538	311	470	866	1993	605	2360	1281	1867
CNRM 8.5	276	571	206	528	331	511	1220	2068	687	2413	1717	2063
MPI 4.5	575	513	586	544	540	448	2326	1843	2301	2373	2634	1777
MPI 8.5	472	533	533	553	497	495	1966	1975	2053	2458	2298	1982
Mean RCP4.5	511	542	476	526	459	484	2070	1920	1755	2318	1833	1883
Mean RCP8.5	70	504	113	552	153	484	300	1925	373	2509	795	1927
Silver birch	S	N	S	N	S	N	S	N	S	N	S	N
CU	425	239	444	226	384	213	1410	622	1577	546	1650	599
HadGEM2 8.5	329	393	307	451	282	402	2058	1280	1501	1797	1647	1336
GFDL 8.5	556	406	556	505	501	378	2693	1464	2241	1716	2548	1370
CanESM2 8.5	423	364	439	466	391	367	2285	1168	1841	1910	2131	1233
MIROC5 8.5	478	434	519	487	444	396	1766	1441	2098	1987	2251	1386
HadGEM2 4.5	546	400	521	418	464	343	2578	1166	2039	1523	2237	1026
CanESM2 4.5	573	391	558	421	530	333	2578	1192	2167	1573	2442	1076
MIROC5 4.5	445	391	545	418	498	333	1755	1569	2144	1622	2363	1144
CNRM 8.5	518	394	553	436	486	353	2413	1749	2579	1955	2726	1423
MPI 4.5	503	349	521	348	504	302	2234	1194	1954	1060	2273	839
MPI 8.5	494	382	559	394	494	325	1802	1068	2111	1357	2238	942
Mean RCP4.5	513	342	500	397	500	299	2463	1244	1913	1405	2361	906
Mean RCP8.5	533	431	569	446	478	389	2465	1365	2145	1712	2323	1266

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