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Temporal and Spatial Change in Diameter Growth of Boreal Scots Pine, Norway Spruce, and Birch under Recent-Generation (CMIP5) Global Climate Model Projections for the 21st Century

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Abstract: We investigated how climate change affects the diameter growth of boreal Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.), and silver birch (*Betula pendula* Roth) at varying temporal and spatial scales. We generated data with a gap-type ecosystem model for selected locations and sites throughout Finland. In simulations, we used the current climate and recent-generation (CMIP5) global climate model projections under three representative concentration pathways (RCPs) forcing scenarios for the period 2010–2099. Based on this data, we developed diameter growth response functions to identify the growth responses of forests under mild (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change at varying temporal and spatial scales. Climate change may increase growth primarily in the north, with a clearly larger effect on birch and Scots pine than Norway spruce. In the south, the growth of Norway spruce may decrease largely under moderate and severe climate change, in contrast to that of birch. The growth of Scots pine may also decrease slightly under severe climate change. The degree of differences between tree species and regions may increase along with the severity of climate change. Appropriate site-specific use of tree species may sustain forest productivity under climate change. Growth response functions, like we developed, provide novel means to take account of climate change in empirical growth and yield models, which as such include no climate change for forest calculations.

Keywords: boreal forest; broadleaves; climate change; conifers; diameter growth; forest calculation; gap-type model; growth response function

1. Introduction

Boreal forests substantially affect the global carbon balance and climate. In northern Europe, these forests are mainly characterized by coniferous species (e.g., Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* (L.)). In addition, deciduous species (e.g., silver birch (*Betula pendula* Roth.)) are present. Growth of the boreal forests is currently limited by the short growing season, low summer temperature, and short supply of nutrients such as nitrogen on upland (mineral) soils and potassium and phosphorus on drained nitrogen-rich peatland (organic) soils [1–4]. However, the changing climate may increase growth in these conditions [3,5–7] due to longer and warmer growing seasons, and increasing decay of soil organic matter and supply of nutrients for growth [2,8]. Furthermore, the increasing atmospheric CO_2 concentration may enhance growth in

boreal forests [3,9–12]. On the other hand, the responses of boreal tree species and forests to climate change largely depend on the prevailing environmental conditions (climate, site) and may therefore vary in different parts of the boreal region. Climate warming and the associated increase in drought, for example, may make growing conditions suboptimal for some tree species but optimal for others [13,14].

In Finland, Norway spruce and silver birch are widely used on upland forest sites of medium and higher fertility, with an adequate supply of nutrients and water, whereas Scots pine is used on upland forest sites of medium or lower fertility and water availability [15]. However, Norway spruce has also been, and is still, extensively cultivated on less fertile sites, which are more optimal for Scots pine. This is partly due to the damage caused by moose and other browsing mammals when grazing amongst young Scots pines and birches in wintertime and eating their shoots [16]. The planting of Norway spruce on less fertile sites may reduce browsing damage. However, it may also reduce forest productivity, particularly in the southern but also in the central boreal region under a warming climate. This is due to increasing drought episodes on soils with a low water-holding capacity [3,17–19]. To date, in the northern boreal region, drought has not been a significant risk for the main tree species.

The projected climate warming in the boreal region is much more rapid than in many other parts of the Earth. This is shown by the most recent-generation (Coupled Model Intercomparison Project Phase 5, CMIP5, see explanation for the Abbreviations in Table A5) global climate model projections under different representative concentration pathways (RCPs) forcing scenarios. In Finland, mean annual temperature is likely to increase by 2–6 °C by 2100. At the same time, mean annual precipitation is likely to increase by 6–18%. Simultaneously the atmospheric CO_2 concentration is predicted to increase up to 430 and 940 ppm in RCP2.6 and RCP8.5 forcing scenarios, respectively, by 2100 [20]. Consequently, there is likely a need to modify current management strategies in order to produce multiple goods and services (e.g., forest biomass, carbon sequestration) in forestry under the changing climate. Proper management strategies may largely depend on tree species, site fertility, geographical region, degree of climate change, and goods and services aimed at in forestry [3,21]. Gradual adaption is crucial due to the large uncertainties involved in future climate change.

The responses of boreal forests to climate change have been intensively studied since the early 1990s. The current understanding of the effects of climate change on the performance of boreal trees is largely based on experiments in growth chambers and greenhouses (e.g., [22–24]). Such experiments have provided valuable information on short-term eco-physiological responses of boreal trees under changing climatic conditions. They have also provided support for forest ecosystem modeling (e.g., [3,25,26]) and for analyzing future growth and development patterns of forests under changing climatic conditions and management. Scenario analyses have also been widely used for identifying the sensitivity of forest production to climate change and management at varying time scales (e.g., [3,5–7,25]), thus outlining the possible need to modify management. However, it is still uncertain how to manage boreal forests in a sustainable way under climate change. Until now, the majority of studies on climate change impacts in boreal forests have been based on the different Special Report on Emissions Scenarios (SRES, CMIP3 database) or older scenarios (e.g., [3,19]).

Forest management planning aims at supporting decision-making by identifying optimal ways to manage forest resources to meet given targets. Empirical growth and yield models have been widely used to assess the effects of management and harvesting intensity on forest growth and wood supply, assuming no change in climate (e.g., [27–29]). Matala et al. [30,31] made the empirical growth and yield model (Motti, e.g., [32]) responsive to climate change by utilizing simulations (photosynthetic production) by an eco-physiological FinnFor model (e.g., [25]). In their approach, the predicted biomass growth under the current climate was corrected for the changing climate by considering changes in atmospheric CO_2 and temperature, but excluding changes in precipitation. In addition, they used characteristics of site, tree stand, and individual trees to predict biomass growth responses. Recently, Pukkala and Kellomäki [33] developed growth trend functions for the diameter growth of Scots pine, Norway spruce, and birch on upland forest sites of varying fertility in the central boreal region in Finland. The data for these functions were generated with a FinnFor model under the gradually

changing climate of the SRES A1B scenario (CMIP3) considering changes in temperature, precipitation, and atmospheric CO_2. Until now, no simple and general approach has been available for assessing the growth and development of boreal forests at varying temporal and spatial scales by employing the most recent-generation CMIP5 global climate model projections under different RCP forcing scenarios.

Diameter and its growth are the key variables in characterizing the size, allometric structure, and growth of trees. In this work, we investigated how climate change may affect the diameter growth of Scots pine, Norway spruce, and birch at varying temporal and spatial scales. We generated diameter and diameter growth data with a gap-type ecosystem model for selected locations and sites throughout Finland under the current climate and mild (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change for the period 2010–2099 (see [20]). Based on this data, we developed functions to quantify diameter growth responses of forests under climate change at varying temporal and spatial scales. The climate change data of the CMIP5 database used in this study indicate greater increases in temperature, but only marginal changes in precipitation, compared with theCMIP3 database. We also demonstrate in this work how the mean climate change of different RCP forcing scenarios may affect diameter growth at a scale ranging from individual trees to the different boreal regions. We assume that our growth response functions may be used in empirical growth and yield models to consider the uncertainties of gradual climate change and its effects on forest production and timber supply.

2. Materials and Methods

2.1. Outlines for Developing Growth Response Functions

We employed a gap-type forest ecosystem model (SIMA model, see [3,26]) to generate the data for development of the functions to analyze the responses of diameter growth (ΔDBH, cm) of boreal Scots pine, Norway spruce, and birch to different climate change projections. The climate change data was based on means of 28 recent-generation (CMIP5) global climate model simulations under the mild, moderate, and severe RCP forcing scenarios (RCP2.6, RCP4.5, and RCP8.5) for the period 2010–2099, as provided by the Finnish Meteorological Institute (Table 3, [20], see explanation for the Abbreviations in Table A5). The current climate data used in the simulations was based on measured temperature and precipitation during the period 1981–2010. We assumed that the response of diameter growth to climate change over time (t) is specific to tree species, site fertility, current climate (temperature sum, TS, threshold > 5 °C, in degree days, d.d.) of the geographical location of site, and climate change projection. The relative diameter growth (ΔDBH$_{rel}$) under the current (cur) and certain climate change (cc) scenarios at the year t under otherwise similar site and tree properties is:

$$\Delta DBH_{rel}(t, cur) = \Delta DBH(t, cur)/DBH = K(t, cur) \times \exp(q(cur) \times DBH), \tag{1}$$

$$\Delta DBH_{rel}(t, cc) = \Delta DBH(t, cc)/DBH = K(t, cc) \times \exp(q(cc) \times DBH), \tag{2}$$

where DBH is the diameter (cm). The values of parameters K and q for the relative diameter growth were estimated for each ten-year sub-period in the period 2010–2099. The values were also estimated separately for each tree species on the southern (61° N), central (63° N), and northern boreal (66° N) sites. In each location, the estimates were further extended over sites of varying fertility, from poor (dry heath, *Calluna* type, CT), through quite poor (dryish heath, *Vaccinium* type, VT) and medium (fresh heath, *Myrtillus* type, MT) to rich (grove-like heath, *Oxalis-Myrtillus* type, OMaT) sites under the mild (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios for 2010–2099. Nevertheless, the values of shape parameter q in Equations (1) and (2) were not affected by climate change. Thus, the multiplier for diameter growth (DBHm(t, cc)) induced by climate change could be written as:

$$DBH_m(t, cc) = K(t, cc)/K(t, cur). \tag{3}$$

In the numerator of Equation (3), the values of K(t, cc) are a nonlinear function of the time since the launch of a certain climate change scenario as estimated separately for each tree species, site type, location, and climate change scenario:

$$K(t, cc) = (a \times t^2 + b \times t + c) - K(t = 1, cc). \tag{4}$$

The location-specific values of parameters a, b, and c were linearly related to the temperature sum (TS, dd.). Thus, these parameters were replaced by the variables: a2 = (p1 × (TS/1000) + p2)/10000; b2 = (p3 − (TS/1000) + p4)/10000 and c2 = (p5 × (TS/1000) + p6)/10000, respectively. The parameter values p1, p6 are shown in Tables A2 and A3 in Appendix A for the upland forest sites (mineral soils) and drained peatlands, separately for each climate change scenario. The initial value of K (t = 1, cc) is subtracted from the calculated K (t, cc) values (t = 2-90), because the changing climate scenarios were initiated from the year 2010 (t = 1) and the current climate represents the average climate for the period 1981–2010.

In the denominator of Equation (3), the values of K (t, cur) were linearly related to the current temperature sum in the locations:

$$K(t, cur) = h \times (TS/1000) + g, \tag{5}$$

where h and g are the parameters (Table A1). TS was divided by 1000 for scaling reasons.

2.2. Data Generation for Development of Growth Response Functions

2.2.1. Outlines of Forest Ecosystem Model Used Simulations

In the data generation, we assumed that the diameter growth (ΔDBH, cm year^{-1}) of a tree is a function of the maximum diameter growth (ΔDBH$_o$, cm year^{-1}, see explanation for the Abbreviations in Table A5). The values of ΔDBH$_o$ are further scaled in the range from 0 to 1 in relation to the temperature sum, prevailing light conditions (M$_L$), soil moisture (M$_W$), and nitrogen supply (M$_N$) to meet the prevailing growing conditions. A value of 1 for any scaling factor or multiplier implies no reduction, while the value of a multiplier < 1 implies a reduction in diameter growth: ΔDBH = ΔDBH$_o$ × M$_{Ts}$ × M$_L$ × M$_w$ × M$_N$. Diameter DBH, cm) is further used to calculate the height (m) of trees and the mass (kg) of different tree organs (foliage, branches, stem, and roots) [3,26]. The values of the maximum diameter growth are also a function of the diameter of trees and the atmospheric carbon dioxide (CO_2, ppm):

$$\Delta DBH_0 = \exp(a + b/(0.01 \times CO_2)) \times DBH \times e^{c \times DBH}, \tag{6}$$

where a, b, and c are the parameters.

The temperature multiplier is based on the temperature sum using a symmetric parabola opening downwards. The minimum and maximum values of temperature sum define the geographical distribution of each tree species in the boreal region (Table 1). The light multiplier is based on the height of each tree, the foliage mass of each tree, the cumulative foliage mass of the foliage of trees taller than a given tree, and the proportion of light from above the canopy penetrating the foliage of taller trees. The light multiplier limits the growth of a tree along with the vertical light gradient within the stand.

Table 1. Temperature sum (TS, d.d.) limits (TS$_{max}$, TS$_{min}$) and the temperature sum for maximum growth (TS$_{opt}$) of different tree species [34].

Tree Species	TS$_{min}$	TS$_{max}$	TS$_{opt}$
Norway spruce	370	2060	1215
Scots pine	390	2500	1445
Silver birch	390	4330	2360

The multiplier for soil moisture indicates the number of dry days in the growing season, and is defined as days with inadequate soil moisture for growth. The multiplier for nitrogen (N) is defined as a function of the N content of foliage, which is further related to the available N (nitrate and ammonium) in soil for uptake by trees. Litter from any living organ and the mortality of whole trees transfer carbon and N into the soil, where litter and humus (soil organic matter) decay, releasing N for reuse in tree growth.

The simulations are run with a time step of one year, and carried out on an area of 100 m^2. The simulations are also based on the Monte Carlo technique, in which each scenario is repeated many times (in this study, 100 times), but only the mean annual values are used in the analyses. In initializing the simulations, the properties of tree stands are described in terms of tree species and the number of trees per hectare in each diameter class. Management options include the planting of seedlings with the desired spacing and tree species, and control of stand density in the tending of seedling stands and in thinning, N fertilization, and the final cut.

Several model validations have demonstrated good agreement between the simulated and the measured mean annual volume growth of Scots pine, Norway spruce, and birch on upland forest sites [3,26]. The model comparison by Routa et al. [35] also indicated good agreement between simulations using the gap-type forest ecosystem model SIMA and the empirical growth and yield model MOTTI [32] for the mean annual volume growth, with and without N fertilization, of managed Norway spruce and Scots pine stands on medium fertile upland forest sites.

2.2.2. Sites and Site Characteristics Used in Simulations

In calculating the effects of different climate change scenarios on growth, the present study considered the change in monthly temperature sums (TS) only for the potential growing season (April to September) compared with the current climate to meet prevailing light conditions, following the approach of Torssonen et al. [19]. The same period was used to calculate the water balance between precipitation and evaporation on the sites. Field capacity and wilting point define the available soil water on different soil and site types (Table 2) and affect the number of dry days (drought episodes) with inadequate soil moisture in the potential growing season [3,26,36,37]. The initial amount of soil organic matter and the N available for growth are defined based on the site fertility type and regional temperature sum of the current climate [3,26].

Table 2. Site type with the volume percent (%) of water for field capacity and wilting point (e.g., [36,37]) and the initial amount of soil organic matter used in the simulations for Northern, Central, and Southern boreal regions of Finland [3]. The regions for soil organic matter represent varying thermal conditions indicated by temperature sum (TS): North < 1000 d.d.; Central = 1000 − 1200 d.d.; and South > 1200 d.d. The upland site types included poor (dry heath, *Calluna* type, CT), quite poor (dryish heath, *Vaccinium* type, VT), medium (fresh heath, *Myrtillus* type, MT) and rich (grove-like heath, *Oxalis-Myrtillus* type, OMaT) sites (see explanation for the Abbreviations in Table A5).

Site Type	Soil Type	Field Capacity, volume % of water	Wilting Point, volume % of water	Initial Amount of Soil Organic Matter, Mg ha^{-1}		
				North	Central	South
OMT	From clay to silty till	40	18	72	76	78
MT	From fine sand to sandy till	25	5	67	70	73
VT–CT	From gravel to sandy till	11	1	56	61	64

2.2.3. Tree Stands Used in Simulations

The simulations for data generation were done for southern (Tampere, 61° N), central (Kuopio, 63° N), and northern (Rovaniemi, 66° N) boreal locations, with temperature and precipitation decreasing from the south to north. In the simulations, three initial stand density classes −450, 900 and 1800 trees per hectare–were used for each stand regardless of tree species. In each case, the tree stand included only trees of the same diameter. From one simulation case to another, the diameter of tree cohorts varied in the range of 5–35 cm with 5 cm intervals. The simulations were run separately in 10-year periods for each 90-year climate change projection (2010–2099). Mortality and regeneration of trees or management were excluded from simulations in order to avoid their effects on model outputs for the sub-periods.

For Scots pine, the calculations were done from poor to rich (CT to OMT) site types, and for Norway spruce and birch from quite poor to rich (VT to OMT) site types. Additional simulations were done by assuming that the soil water availability does not limit growth (growth multiplier M_W = 1), as is the case on drained peatland sites with comparable site fertility. Further simulations were done by assuming a fixed CO_2 concentration of 350 ppm, while otherwise using the climate scenario–specific (RCP2.6, RCP4.5, and RCP8.5) changes in temperature and precipitation. This was done in order to separately evaluate the impacts of atmospheric CO_2 elevation on the growth responses. In all simulations, atmospheric N deposition of 10 kg N ha^{-1} year^{-1} was used [26].

2.2.4. Climate Scenarios Used in Simulations

The current climate data used in simulations is based on the measurements conducted by the Finnish Meteorological Institute for temperature and precipitation during the reference period (1981–2010). The climate change data was also downloaded from the Coupled Model Intercomparison Project Phase 5 (CMIP5) database by the Finnish Meteorological Institute. Climate change data represents the means of 28 recent-generation (CMIP5) global climate model simulations under the RCP2.6, RCP4.5, and RCP8.5 forcing scenarios (Table 3, see explanation for the Abbreviations in Table A5). These datasets comprise the projected change in monthly mean temperature and precipitation along with the annual change in atmospheric CO_2 for the sub-periods 2010–2039, 2040–2069, and 2070–2099.

Table 3. Average changes in temperature (ΔT, °C), precipitation (ΔP, %), average temperature sum (TS, d.d.) and atmospheric CO_2 (ppm) level under minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios for the periods 2010–2039, 2040–2069, and 2070–2099. The atmospheric CO_2 (ppm) level obtained by 2100 is shown in parentheses.

Scenario	RCP2.6			RCP4.5			RCP8.5		
	2010–2039	2040–2060	2070–2099	2010–2039	2040–2069	2070–2099	2010–2039	2040–2069	2070–2099
ΔT (°C)	1.3	1.9	1.9	1.4	2.5	3.3	1.5	3.4	5.5
TS (d.d.)	1189	1286	1296	1207	1375	1474	1231	1532	1845
ΔP (%)	4.3	5.9	6.2	4.0	7.6	10.7	5.4	11.1	18.4
CO_2 (ppm)	417	456	446 (430)	422	495	532 (538)	432	572	803 (936)

The observational and climate change data were both interpolated onto a 10 km × 10 km grid using the kriging with external drift (KED) method [38]. By 2070–2099, the annual mean temperature is expected to increase by 1.9–5.5 °C and the precipitation by 6.2–18.4% when the atmospheric CO_2 content increases to 446–803 ppm under the RCP2.6 and RCP8.5 scenarios, compared to the current climate with an atmospheric CO_2 content of 350 ppm (Table 3). The RCP2.6, RCP4.5, and RCP8.5 scenarios represent minor, moderate, and severe climate change in relation to the current climate, respectively. Figure 1 shows the projected changes in the temperature sum, indicating the combined effects of the length and thermal conditions of the growing season.
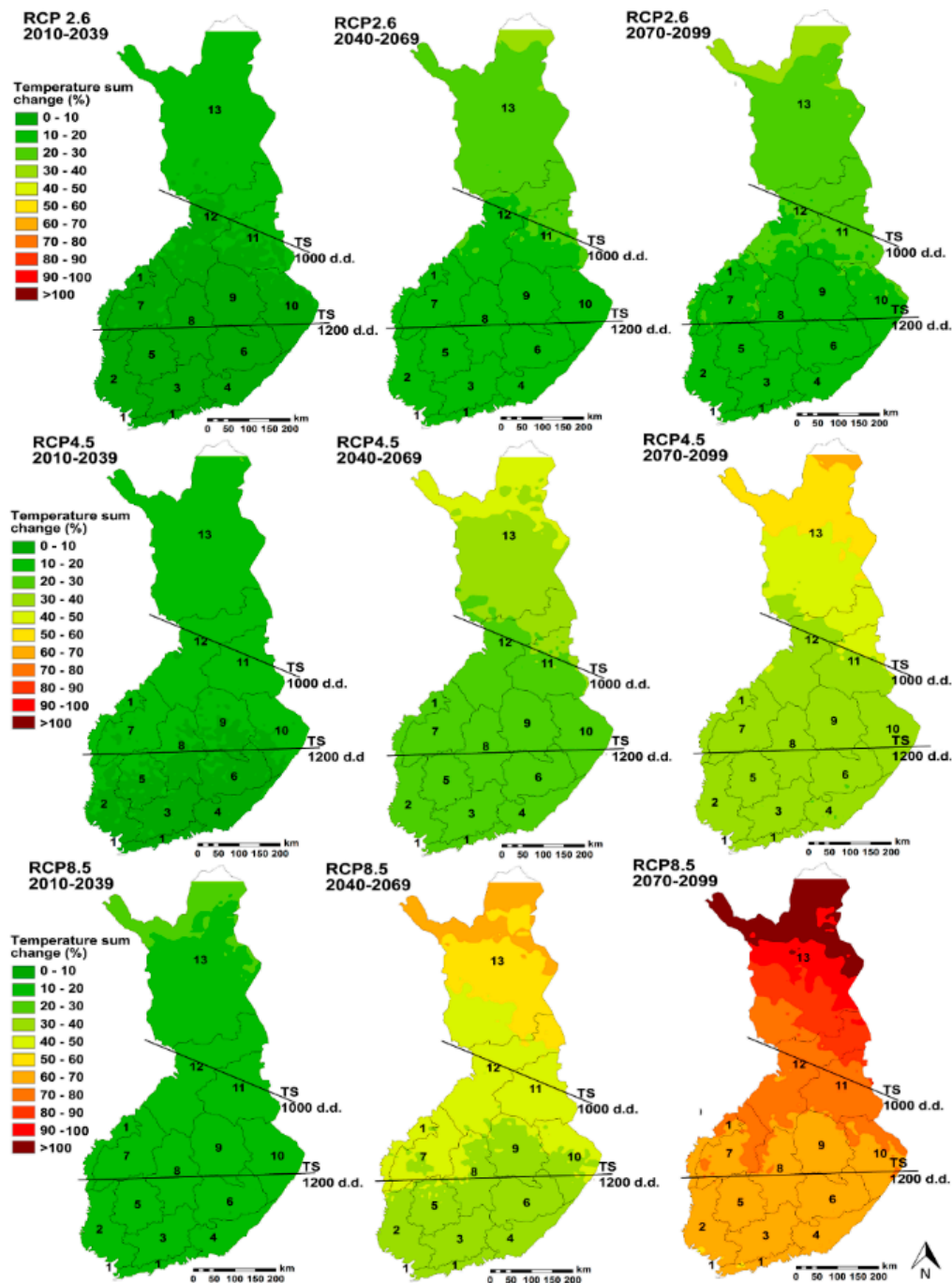
Figure 1. Predicted changes in temperature sum (TS) under the minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios for the sub-periods 2010–2039, 2040–2069, and 2070–2099. The temperature sum lines across the country separate the southern (TS > 1200 d.d.), central (1000 d.d. < TS < 1200 d.d.), and northern (TS < 1000 d.d.) boreal regions.

2.3. Performance and Generalization of Calculations by Diameter Growth Response Functions

First, we studied the sensitivity of growth responses to climate change scenarios, water availability, and elevation of the atmospheric CO_2 level. These analyses were carried out for different tree species on different southern (Tampere, 61° N) and northern (Rovaniemi, 66° N) boreal sites (VT and MT upland sites and corresponding peatland sites drained for forestry) over the period 2010–2099.

Secondly, we studied how the diameter growth responses change over all upland site types in different boreal regions. The mean growth responses of different tree species were calculated separately for the southern (TS > 1200 d.d.), central (1000 d.d. < TS < 1200 d.d.), and northern (TS < 1000 d.d.) boreal regions under different RCP scenarios over the period 2010–2099.

Thirdly, the findings were averaged throughout the country. In this case, one randomly selected sample plot of each cluster for the permanent sample plots of the National Forest Inventory (NFI11, 2009–2013) was used in data analyses. These sample plots were located on upland forest sites and assigned to timber production (Table 4). In the NFI11, the average distance between clusters of sample plots is 6 × 6 km across the whole of country, except the northernmost region (Forestry Centre unit 13), where it is 10 × 10 km. Variables recorded for all sample trees included tree species and diameter at breast height (at 1.3 m height). We calculated the diameter growth responses on each plot in two phases, including species-by-species calculations based on their presence, and further basal-area-weighted growth response calculations over all trees (on average, nine trees per plot) and species per plot.

Table 4. Number (%) of sample plots of the National Forest Inventory (NFI11) on different upland forest sites for southern (old Forestry Centre units 1–6), central (7–10), and northern (11–13) boreal regions. The upland site types included poor (dry heath, *Calluna* type, CT), quite poor (dryish heath, *Vaccinium* type, VT), medium (fresh heath, *Myrtillus* type, MT), and rich (grove-like heath, *Oxalis-Myrtillus* type, OMaT) sites.

Upland Forest Sites	Total Number (% of All Plots in the Parenthesis)			
	South	Central	North	Total
CT	17 (2)	34 (4)	22 (4)	73 (3)
VT	116 (15)	252 (26)	179 (31)	547 (24)
MT	345 (46)	461 (48)	353 (62)	1159 (51)
OMT	280 (37)	206 (22)	15 (3)	501 (22)
Total	758 (100)	953 (100)	569 (100)	2280 (100)

3. Results

3.1. Performance of Diameter Growth Response Functions in Different Tree Species on Varying Site Types

Under different RCP scenarios and 30-year calculation periods, diameter growth in Scots pine increased by up to 10–16% on the medium fertile (MT) sites in the south, and by up to 34–94% in the north (Figure 2; Table 5). On the other hand, the growth decline initiated in the south after the first 30- to 60-years, depending on the RCP scenario. However, during the last 30-year period, the growth increase in the south was still on average 7–13% higher under RCP2.6 and RCP4.5 than under the current climate, but 29% lower under RCP8.5. Growth also showed a slight decline in the north under RCP2.6 during the last 30-year period.

On the medium fertile (MT) sites, growth in Norway spruce increased markedly less than in Scots pine (Figure 2; Table 5). In addition, growth increased only in the north, up to 14–27% under different RCP scenarios compared to the current climate. During the last 30-year period, growth declined slightly in the north under RCP2.6 and RCP4.5. Under RCP8.5, it declined largely and was up to 7% lower than under the current climate. In the south, growth decreased under the changing climate compared to the current climate during the first 30- to 60-years, being there up to 3–12% lower depending on the RCP scenario. During the last 30-year period, growth in the south was 10–95% lower than under the current climate.

On the medium fertile (MT) sites, growth in birch increased significantly more than in Scots pine and Norway spruce, by up to 21–76% over different 30-year periods in the south, and by 41–167% in the north under different RCP scenarios (Figure 2; Table 5). Additionally, in birch, growth declined slightly in the south under RCP2.6 during the last 30-year period.
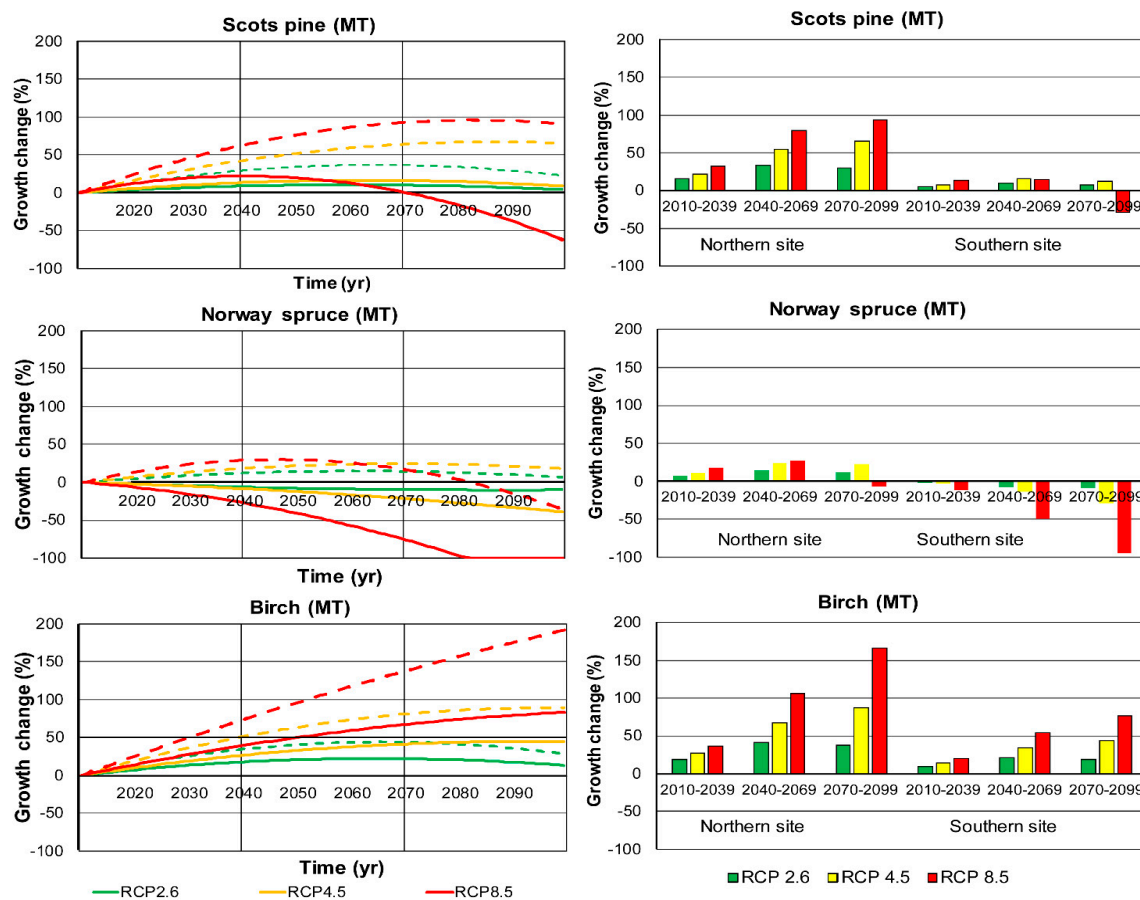
Figure 2. Left: Percentage change of diameter growth response for different tree species over time on the upland medium fertile (MT) sites under minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios in relation to the current climate. Dotted lines indicate the changes in the north (Rovaniemi, 66° N) and solid lines in the south (Tampere, 61° N). **Right**: Mean percentage change of diameter growth for different tree species on MT sites for 2010–2039, 2040–2069, and 2070–2099 in the north and south on MT sites under different RCPs in relation to the current climate.

Regardless of tree species, the pattern of growth change on poor and quite poor (VT and CT) sites was similar to that on the medium fertile and rich sites (MT and OMT have very similar patterns). However, the increase in growth was smaller and decline in growth larger (see Table 5; Appendix A Tables A1 and A2, parameters of growth response functions). The effects of reduced water supply on growth can also be seen in Table 5.

3.2. Effects of Soil Water Availability and Atmospheric CO$_2$ Level on Calculated Growth Responses

Figure 3 (left panel) shows the differences in the calculated growth responses over the whole 90-year period under different RCP scenarios when including or excluding the effects of shortage of soil water on growth. In the former case, the calculations were done for the upland sites (VT and MT sites, Mw < 1) and in the latter case for the drained peatland sites, assuming the same site fertility as in the upland case (but Mw =1). Growth on the drained peatland sites was up to 6–7% higher in Scots pine and Norway spruce, and up to 18% higher in birch, than on the upland sites. The effect of reduced water supply (drought) was clear in the south, but marginal in the north.

Table 5. Mean change in diameter growth on quite poor (VT) and medium fertile (MT) upland sites in different tree species in the south (Tampere, 61° N) and north (Rovaniemi, 66° N) under minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios in relation to the current climate. Numbers in parentheses indicate response for corresponding peatland sites (no drought).

Climate Scenario	Change in Diameter Growth Under Climate Change, % of that Under Current Climate					
	Scots Pine		Norway Spruce		Silver Birch	
	North	South	North	South	North	South
RCP2.6:	Quite poor site (VT)					
2010–2039	15 (16)	2 (5)	4 (7)	−8 (−3)	16 (20)	5 (10)
2040–2069	32 (34)	5 (11)	8 (15)	−17 (−7)	35 (44)	12 (22)
2070–2099	28 (31)	3 (8)	6 (11)	−16 (−9)	32 (40)	11 (20)
2010–2099	25 (27)	3 (8)	6 (11)	−13 (−6)	28 (35)	9 (18)
	Medium fertile site (MT)					
2010–2039	16 (16)	5 (5)	7 (7)	−3 (−3)	19 (19)	10 (10)
2040–2069	34 (34)	10 (10)	14 (14)	−8 (−8)	41 (41)	21 (21)
2070–2099	30 (30)	7 (7)	11 (11)	−10 (−10)	37 (37)	18 (18)
2010–2099	27 (27)	7 (7)	11 (11)	−7 (−7)	33 (33)	16 (16)
RCP4.5:	Quite poor site (VT)					
2010–2039	21 (23)	4 (8)	6 (11)	−9 (−3)	22 (28)	8 (15)
2040–2069	50 (56)	7 (17)	11 (24)	−26 (−13)	55 (72)	19 (38)
2070–2099	58 (58)	4 (14)	6 (24)	−0 (−29)	67 (92)	26 (48)
2010–2099	43 (49)	5 (13)	8 (19)	−25 (−15)	48 (64)	18 (34)
	Medium fertile site (MT)					
2010–2039	22 (22)	7 (7)	10 (10)	−4 (−4)	27 (27)	14 (14)
2040–2069	55 (55)	16 (16)	23 (23)	−14 (−14)	68 (68)	35 (35)
2070–2099	66 (67)	13 (13)	22 (22)	−30 (−30)	87 (87)	44 (44)
2010–2099	48 (48)	12 (12)	18 (18)	−16 (−16)	61 (61)	31 (31)
RCP8.5:	Quite poor site (VT)					
2010–2039	31 (34)	8 (15)	9 (18)	−20 (−11)	30 (38)	12 (21)
2040–2069	68 (83)	−2 (17)	3 (28)	−63 (−48)	74 (114)	19 (60)
2070–2099	64 (99)	−55 (−28)	−41 (−5)	−98 (−95)	91 (183)	1 (92)
2010–2099	54 (72)	−17 (1)	−10 (14)	−61 (−52)	65 (112)	10 (58)
	Medium fertile site (MT)					
2010–2039	33 (33)	14 (14)	18 (18)	−12 (−11)	37 (37)	20 (20)
2040–2069	80 (80)	15 (16)	27 (27)	−49 (−49)	106 (106)	54 (55)
2070–2099	94 (96)	−29 (−28)	−7 (−7)	−95 (−95)	167 (167)	76 (82)
2010–2099	69 (70)	0 (0)	12 (12)	−52 (−52)	104 (104)	50 (53)

Furthermore, Figure 3 (right panel) shows the differences in growth over the whole 90-year period, with a fixed level of atmospheric CO_2 (350 ppm) and gradually increasing atmospheric CO_2 levels used for different RCP scenarios. In both cases, temperature and precipitation changed over time, as in each RCP scenario, thus enabling an assessment of how elevated CO_2 alone may affect diameter growth. Under RCP2.6, the gradually increasing CO_2 increased growth by up to 3–4%, regardless of tree species and location. Similarly, under RCP4.5, growth increased by up to 7–9% in the south and 10–14% in the north. Under RCP8.5, growth increased by up to 5–15% in the south and 20% in the north. The increase was higher for Scots pine and birch than for Norway spruce.
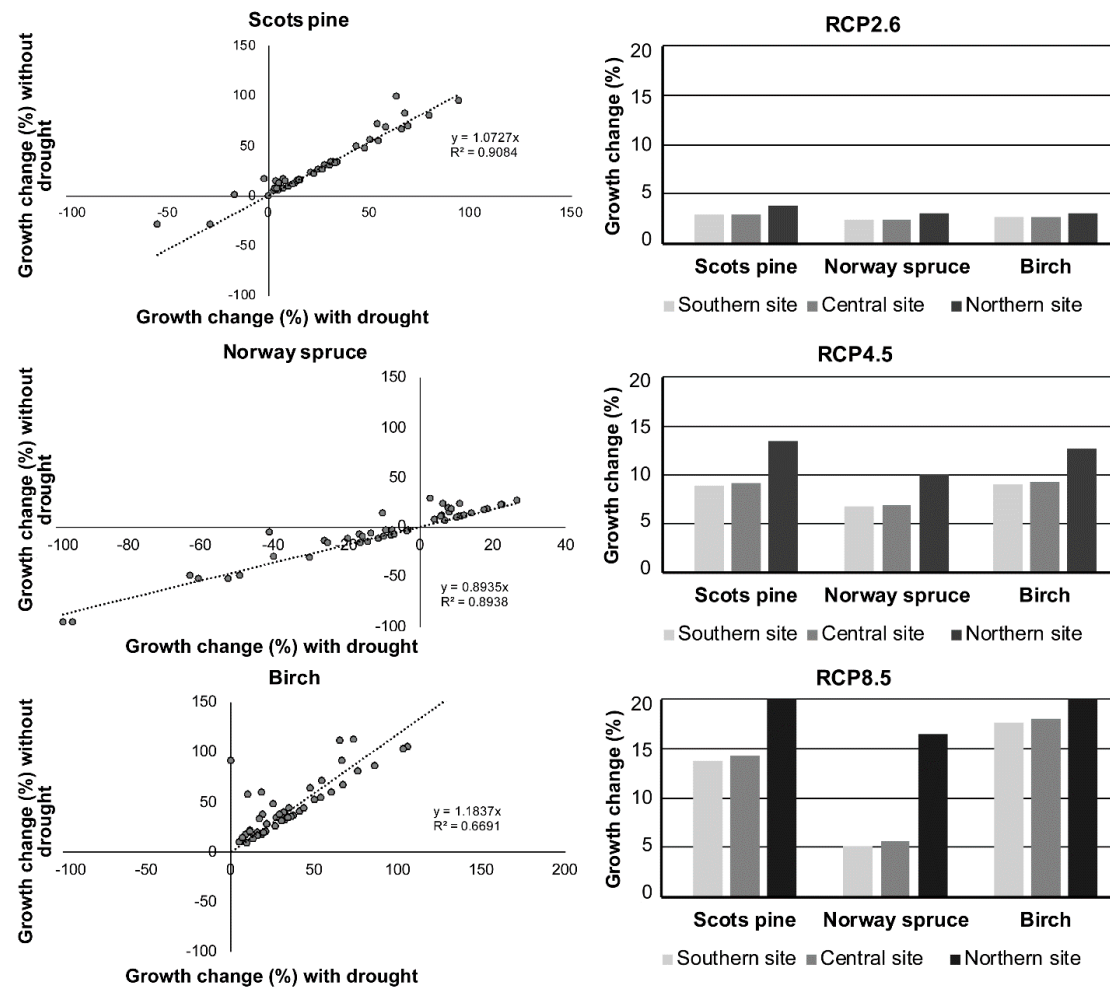
Figure 3. Left: The relationship for change (%) of diameter growth responses of Scots pine, Norway spruce, and birch when including (x-axis) and excluding (y-axis) the effects of drought on growth responses on quite poor and medium fertile (VT and MT) upland sites and corresponding drained peatland (Vtkg and Mtkg) sites, under minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change. The data points in the upper-right quadrant represent the sites in the north (Rovaniemi, 66° N), while those in lower left represent the sites in the south (Tampere, 61° N) over three 30-year periods. **Right:** The differences (%) in diameter growth responses in Scots pine, Norway spruce, and birch on medium fertile (MT) sites over the whole 90-year period with a fixed level of atmospheric CO_2 (350 ppm), and the gradually increasing CO_2 levels for each RCP scenario. The temperature and precipitation changes were specific to each RCP scenario in calculations on the southern (Tampere, 61° N), central (Kuopio, 63° N), and northern (Rovaniemi, 66° N) boreal sites.

3.3. Tree Species-Specific Growth Responses Over All Upland Sites in Different Temperature Regions

Figure 4 shows the average percentage changes in the mean diameter growth for Scots pine, Norway spruce, and birch over all upland forest sites (on NFI11 plots) for the southern (TS > 1200 d.d.), central (TS 1000–1200 d.d.), and northern (TS < 1000 d.d) boreal regions. In the first 30-year calculation period, the mean growth in Scots pine increased compared to the current climate by up to 2–11% in the southern and central boreal regions, and by up to 10–20% in the northern boreal region, depending on the RCP scenario. In the second 30-year period, it increased by up to 5–23% in the southern and central regions, and by up to 28–61% in the northern region. In the third 30-year period, the mean growth increased by 4–22% in the southern and central region and by 28–55% in the northern region, under

both RCP2.6 and RCP 4.5. Under RCP8.5, it also increased in the north by up to 65%, but decreased in other regions by up to 6–39%, with the south showing the greatest decline.
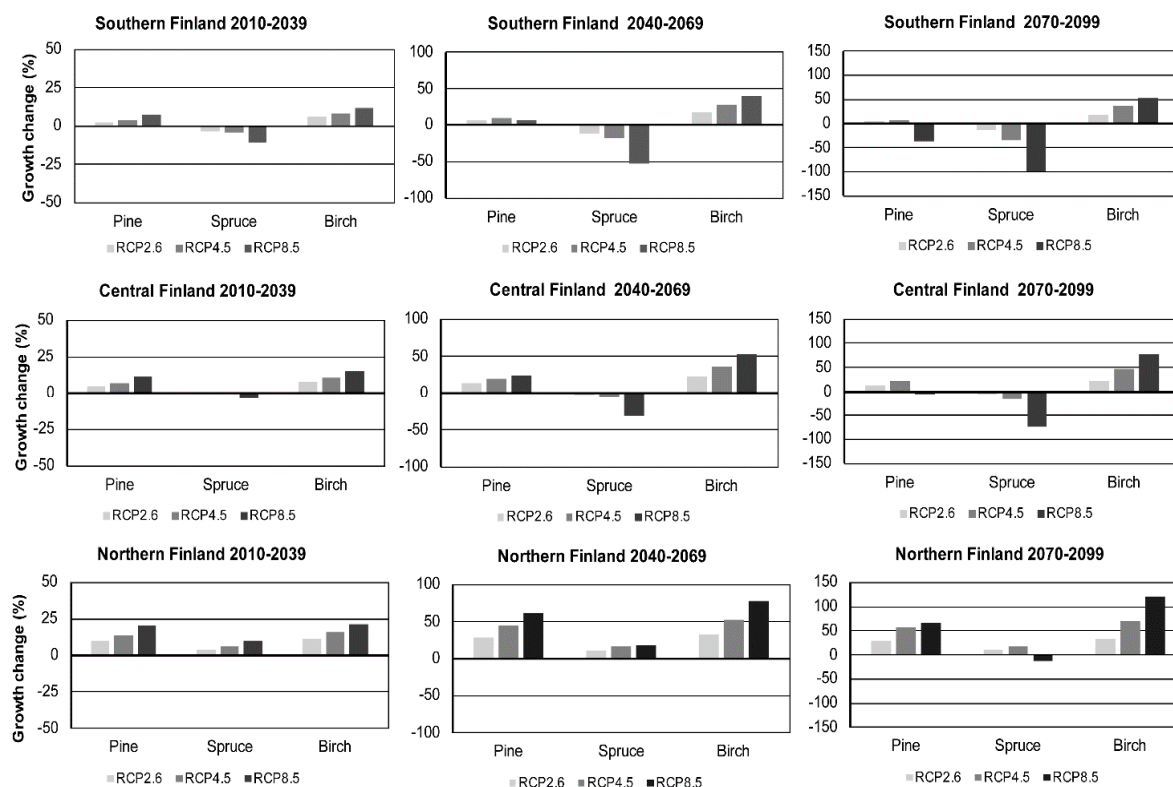

Figure 4. Average percentage changes in the diameter growth of Scots pine, Norway spruce, and birch on the upland forest sites (NFI11 plots) in different temperature sum (southern TS > 1200 d.d., central 1000 d.d. < TS < 1200 d.d. and northern TS < 1000 d.d.) regions in three 30-year sub-periods over the years 2010–2099 under minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios. If drained peatland sites were included in these calculations, the positive growth responses would have been slightly higher and the negative ones lower (see, e.g., Table 5).

In contrast to Scots pine, in the first 30-year calculation period in the southern boreal region, the mean growth of Norway spruce was already up to 4–11% lower under different RCP scenarios than under the current climate. In the second and last 30-year periods, the mean growth of Norway spruce was up to 12–53% and 14–100% lower (with the largest decrease being under RCP8.5). The mean growth reduction in Norway spruce in the last 30-year period was lower, by 6–75%, in the central region than in the southern one. In the northern region, the mean growth in Norway spruce increased from the first to the last 30-year period under both RCP2.6 and RCP4.5, from 4–6% to 9–16%, compared to the current climate. The same was true for the first and second 30-year periods under RCP8.5, in which growth exceeded the current climate levels by up to 9–17%. But growth declined in Norway spruce by up to 14% in the third 30-year period under RCP8.5. Compared to Scots pine and Norway spruce, the mean growth of birch increased significantly more under the changing climate throughout the 90-year calculation period. The growth increase was the highest in the north and under RCP8.5. The mean growth increased in birch compared to the current climate by up to 6–12% in the first 30-year period and by up to 16–52% in the third 30-year period in the southern region. Corresponding changes were 11–21% and 33–119% in the northern region.

3.4. Growth Responses Over All Upland Forest Sites in Different Temperature Regions

Figure 5 shows that, across the whole country, mean forest growth may decline on 20% of the upland forest inventory plots by 2040–2070, assuming minor (RCP2.6) or moderate (RCP4.5) climate change. If severe climate change (RCP8.5) is assumed, the number of such cases increases to 30%. In the last 30-year period (2070–2099), the percentage of cases with declining forest growth increases substantially, being over 60% under the severe climate change scenario.
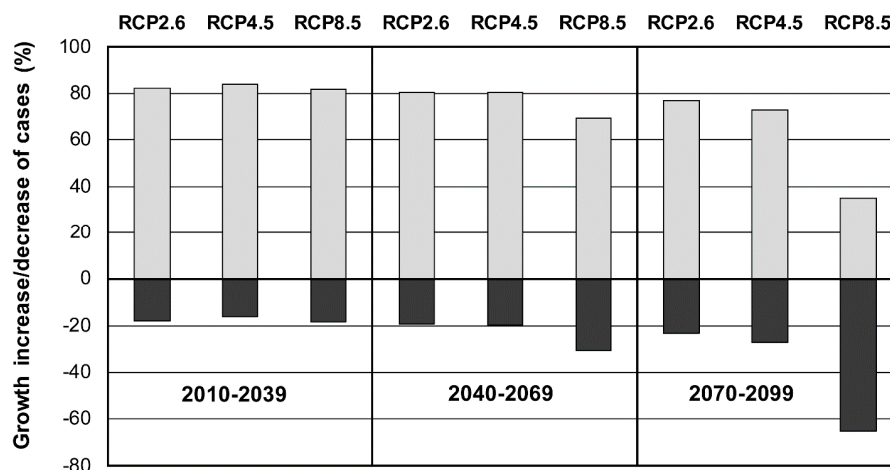

Figure 5. Percentage distribution of declining and increasing growth changes of the total number of cases for minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios over all upland forest inventory plots for different 30-year calculation periods (2010–2039, 2040–2069, and 2070–2099) across the whole country. If drained peatland sites were included in calculations, positive responses of growth would have been slightly higher and negative responses lower (see Table 5).

Table 6 and Figure 6 show that mean forest growth may increase significantly more in the northern (on NFI11 plots) than in the southern boreal region, regardless of the RCP scenario. Under RCP2.6, mean forest growth may increase throughout the country, while it may decrease substantially towards 2100 under RCP4.5, and especially under RCP8.5, particularly in the south. However, also in the central boreal region, forest growth may decline slightly under the RCP8.5 scenario in the last 30-year period (Table 6).

Table 6. Mean change (%) in the diameter growth (% of that under the current climate) of all tree species on upland forest sites under minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios for three 30-year calculation periods for the current temperature sum (TS) regions representing southern, central, and boreal regions. The numbers in parentheses indicate the standard deviation of growth change. If drained peatland sites were included in these calculations, the positive responses of growth would have been slightly higher and the negative ones lower (see, e.g., Table 5).

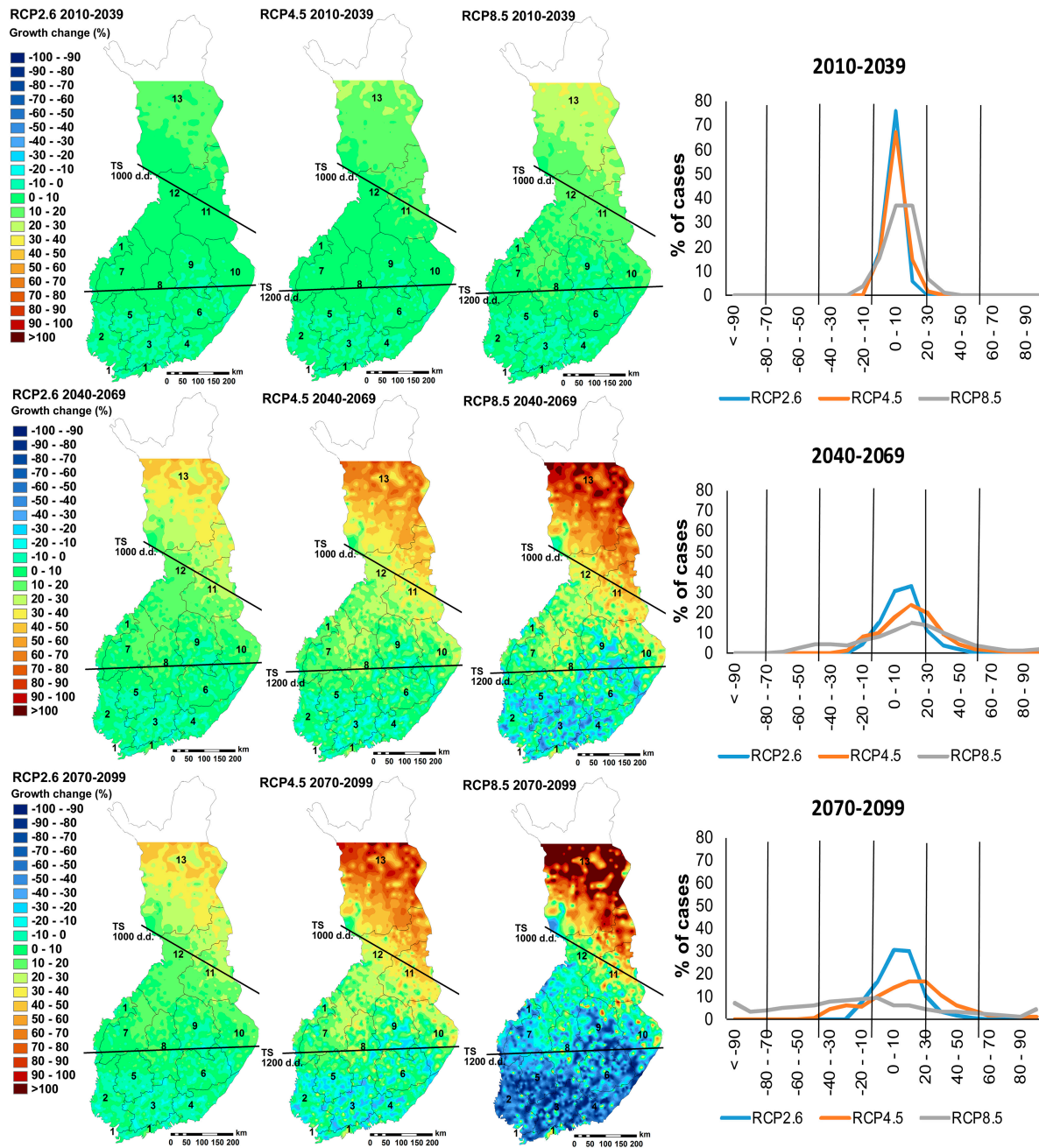| TS Region	RCP2.6, Mean Growth Response Change (%)			RCP4.5, Mean Growth Response Change (%)			RCP8.5, Mean Growth Response Change (%)		
Period	2010–2039	2040–2069	2070–2099	2010–2039	2040–2069	2070–2099	2010–2039	2040–2069	2070–2099
Southern boreal, TS > 1200 d.d.	0.2 (2.8)	−0.1 (8.3)	−1.6 (8.7)	0.7 (3.7)	−0.2 (13.2)	−7.0 (19.9)	0.5 (7.9)	−13.4 (27.4)	−52.9 (38.9)
Central boreal, TS 1000-1200 d.d.	3.2 (2.4)	8.9 (7.2)	7.7 (7.5)	4.7 (3.2)	13.7 (11.4)	12.8 (16.8)	7.4 (6.0)	11.1 (21.7)	−20.1 (34.5)
Northern boreal, TS < 1000 d.d.	8.5 (3.3)	24.9 (9.7)	24.2 (10.1)	12.0 (4.5)	38.6 (15.3)	47.4 (21.3)	18.2 (6.1)	52.9 (25.0)	50.2 (45.4)
Across the whole boreal region	3.5 (4.0)	10.1 (12.1)	8.9 (12.5)	5.3 (5.5)	15.5 (18.9)	15.2 (27.0)	8.0 (9.1)	13.9 (33.8)	−13.1 (53.5)

Figure 6. Left: Spatial distribution of the mean increase in diameter growth over all tree species on upland forest sites for different 30-year calculation periods (2010–2039, 2040–2069, and 2070–2099) under the minor (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios. The numbers in the figures indicate the old administrative forest center regions. **Right**: Percentage distribution of changes in growth responses in relation to total number of cases, for different 30-year periods and RCP scenarios, across the whole country. If drained peatland sites were included in calculations, positive responses of growth would have been slightly higher and the negative ones lower (see Table 5).

4. Discussion and Conclusions

Empirical growth and yield models assuming no climate change are widely used to support decision-making in forestry. However, under the changing climate, the responses of trees and forests may change largely compared to that under the current climate. Responses to climate change may also differ largely depending on tree species, site properties, geographical region, and the severity of

climate change. Use of empirical growth and yield models assuming no climate change is likely to cause large uncertainties in the calculations on the growth and development of forest resources and timber supply under climate change. Therefore, they are not anymore applicable for forest calculations as such, especially if climate change proceeds rapidly. On the other hand, in empirical growth and yield models, diameter and its growth are the key variables in characterizing the size, structure, and growth of trees. Thus, these variables may be used to ascertain the impacts of climate change on forest growth by utilizing empirical growth and yield models with growth response functions taking account of climate change.

In this work, we developed tree species-specific response functions for diameter growth for boreal Scots pine, Norway spruce, and birch to identify their growth responses under climate change at varying temporal and spatial scales. This was done based on data generated with a well-validated gap-type ecosystem model SIMA. Using growth response functions, we calculated how the mild (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios may affect diameter growth in the scale from individual trees to the different boreal regions (on NFI11 plots). The climate change scenarios used indicate in the worst case (RCP8.5) even greater increases in temperature and marginal changes in precipitation, compared with previous ones used in the earlier development of growth response functions [30,31,33]) and climate change impact studies (e.g., [3,33,39–41]). The earlier response functions were also based on climate scenarios, which excluded any leveling off or even decline in temperature due to the decline of greenhouse gases by the end of the century as was observed under the RCP2.6. Therefore, there was a clear need to develop new growth response functions, which are applicable at wide temporal and spatial scales, considering different concentration pathways (RCP) forcing scenarios.

Our study demonstrated that climate change might increase the growth of boreal tree species in the north, and substantially more in birch and Scots pine than Norway spruce. In the south, the growth may decrease largely, especially in Norway spruce, but partially also in Scots pine, in contrast to that of birch. The degree of differences between tree species, site types, and boreal regions tends to increase along with the severity of climate change. Ruosteenoja et al. [20] stated that frequency and length of drought periods might increase in spring and summer, especially under severe climate warming. A simultaneous increase in summer temperatures and drought episodes may make growing conditions sub-optimal for some tree species and more optimal for others (e.g., [13,42–46]).

According to Peng et al. [43], the mortality of trees in the Canadian boreal forests (on permanent sample plots) increased by 5% in 1963–2008 due to increasing drought episodes (e.g., [47]). Based on previous experimental studies, tree growth may also decline and mortality increase in boreal forests located in northern and eastern Europe under higher summer temperatures and longer drought (e.g., [17,18,42,48,49]). When excluding the shortage of water supply, Peltola et al. [10] and Kilpeläinen et al. [50] found that the diameter growth of young boreal Scots pines increased by 26% and 67%, when trees were grown in climate chambers with elevated temperature (T + 4 °C) alone or combined with doubled CO_2, compared to the current (ambient) climate. However, when using eco-physiological models with a short time resolution (e.g., daily time resolution), the predicted growth increases and decreases are more conservative under climate change, being up to 15–30% (e.g., [30]), regardless of tree species.

The tree species composition and growing conditions (climate, site types) vary largely between different boreal regions in Finland, which explains large spatial variability in growth responses over the country during the period of 2010–2099. Under mild climate change (RCP2.6), mean forest growth may increase throughout the country, whereas under moderate (RCP4.5) and especially severe climate change (RCP8.5), the situation may be opposite, particularly in the southern boreal region. Across the whole country, mean forest growth may decline on up to 30% of the forest inventory plots, depending on the severity of climate change by 2040–2069. The percentage of plots with declining growth may exceed 60% under the severe climate change in the period of 2070–2099.

Similar to the effects of minor climate change (RCP2.6), but ignoring the effect of CO_2 fertilization, the growth of Scots pine increases based on the findings of provenance trials when transferring southern provenances slightly northwards (i.e., one to two latitudes, e.g., [51–53]). Nevertheless, such transfer response is smaller than shown in our calculations. On the other hand, we did not consider the genetic differences within tree species. Climate warming is also likely to affect the growth and survival of trees depending on the geographical location (and prevailing temperature sum) of the site to which the sub-populations of each tree species were originally adapted [53,54]. Even minor climate warming likely enhances the growth and survival of tree species such as Scots pine in northern Europe (>62° N), but reduces them at lower latitudes [54]. Based on a meta-analysis of experiments with elevated CO_2 and temperature, Stinziano and Way [55] suggested that the biomass growth of boreal trees might increase if the annual mean temperature increase remains below 5 °C.

To conclude, the growth responses of boreal forests are dependent on the severity of climate change, tree species, and local climatic and site conditions, as well as on forest management. Currently, forest management in boreal forests is strongly focused on conifers [56]. However, our results suggest that we should in future favor Scots pine and birch or mixtures of conifers and broadleaves, especially in the southern boreal region. In this way, the recreational and biodiversity values of forests may also be increased [56]. On the other hand, the growth in Scots pine may also decline under severe climate change (RCP8.5) in the south. This was not evident based on earlier impact studies employing climate data of the CMIP3 database. Climate change likely also increases abiotic and biotic damages (e.g., [57–61]), which may partially counteract the positive effects of climate change on forest growth and timber supply (e.g., [62,63]). However, we did not consider them in our study. Many questions remain open about how to manage boreal forests (e.g., region-and site-specific use of different tree species and genotypes) in a sustainable way to meet the challenges of climate change. The growth response functions, as we developed, provide novel means to take account climate change at different spatial and temporal scales in empirical growth and yield models, which as such do not consider climate change in simulations of growth and development of forest resources. Consideration of climate change is crucial in forestry because the responses of trees and forests may change largely compared to that under the current climate. Our growth response functions are based on diameter and its growth, which are key variables in empirical growth and yield models. Therefore, our approach does not disturb the dynamics of such models as it only corrects the diameter predicted under the current climate to meet climate change. This approach could be easily used also in other regions, where conventional forest inventory data and necessary climate datasets are available.

Author Contributions: Seppo Kellomäki and Heli Peltola designed the study; Seppo Kellomäki and Harri Strandman analyzed the data and developed the growth response functions; Harri Strandman created all figures; Seppo Kellomäki and Heli Peltola were primarily responsible for writing the paper; and other co-authors participated in the writing of manuscript mainly by editing it and commenting thereon.

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

Appendix A

Table A1. Parameters used in Equation (5) on upland sites (mineral soils) and drained peatland sites with comparable fertility. Legends: The upland site types included poor (dry heath, *Calluna* type, CT), quite poor (dryish heath, *Vaccinium* type, VT), medium (fresh heath, *Myrtillus* type, MT), and rich (grove-like heath, *Oxalis-Myrtillus* type, OMaT) sites. Vtkg, Ptkg, Mtkg, and Rtkg are drained peatland sites with fertility comparable to that of CT, VT, MT, and OMT upland sites.

Site Type	Scots Pine		Norway Spruce		Silver Birch	
	h	g	h	g	h	g
Upland sites						
CT	0.0646	0.0137	-	-	-	-
VT	0.1041	0.0038	−0.0085	0.0954	0.144	−0.0075
MT	0.1687	−0.0184	0.0484	0.0916	0.2946	−0.0866
OMT	0.1712	−0.016	0.0452	0.1057	0.2942	−0.0783
Drained peatlands						
Vtkg	0.1178	−0.018	-	-	-	-
Ptkg	0.1359	−0.015	0.0422	0.0725	0.2509	−0.0812
Mtkg	0.1678	−0.0184	0.0495	0.0934	0.2957	−0.0875
Rtkg	0.1751	−0.0193	0.05	0.0992	0.3053	−0.0892

Table A2. Parameters used in Equation (4) for climate change (cc) scenarios on poor (dry heath, *Calluna* type, CT), quite poor (dryish heath, *Vaccinium* type, VT), medium (fresh heath, *Myrtillus* type, MT), and rich (grove-like heath, *Oxalis-Myrtillus* type, OMaT) upland sites.

Climate Scenario	Scots Pine	a2		b2		c2	
		p1	p2	p3	p4	p5	p6
RCP2.6	CT	0.1562	−0.2046	−17.896	22.988	643.05	212.55
	VT	0.206	−0.2792	−23.388	31.087	968.23	222.50
	MT	0.1915	−0.3104	−23.106	35.773	1623.9	34.376
	OMT	0.2236	−0.3426	−26.439	39.088	1657.8	66.837
RCP4.5	CT	0.1483	−0.2001	−23.921	30.518	642.17	204.57
	VT	0.1587	−0.2425	−29.436	40.143	985.95	188.12
	MT	0.0893	−0.2184	−27.357	44.775	1634.7	6.8017
	OMT	0.1393	−0.272	−32.986	50.668	1686.9	16.27
RCP8.5	CT	−0.1148	−0.0588	−24.6	36.728	656.63	179.17
	VT	−0.2492	0.0035	−27.493	46.536	966.65	184.04
	MT	−0.6133	0.2933	−14.265	44.409	1549.70	41.965
	OMT	−0.5683	0.2307	−22.057	52.706	1609.20	48.241

Climate Scenario	Norway Spruce	a2		b2		c2	
		p1	p2	p3	p4	p5	p6
RCP2.6	VT	0.2034	−0.2004	−22.120	21.510	−148.95	1059.0
	MT	0.2686	−0.3012	−31.109	33.874	337.88	1165.1
	OMT	0.3292	−0.3578	−37.18	39.483	283.49	1338.4
RCP4.5	VT	0.1668	−0.1869	−26.877	26.874	−145.24	1048.2
	MT	0.1427	−0.2138	−37.664	42.726	350.68	1144.3
	OMT	0.2115	−0.2801	−45.614	50.175	313.75	1295.6
RCP8.5	VT	0.4336	−0.5408	−53.814	53.912	30.729	889.68
	MT	0.3541	−0.6056	−82.361	91.39	666.87	832.03
	OMT	0.5009	−0.7637	−94.934	103.63	640.05	973.55

Climate Scenario	Birch	a2		b2		c2	
		p1	p2	p3	p4	p5	p6
RCP2.6	VT	0.185	−0.2924	−20.643	32.65	1457.6	44.237
	MT	0.0677	−0.2867	−8.8892	33.013	3017.4	−689.33
	OMT	0.151	−0.3643	−17.819	41.392	3020.8	−609.36
RCP4.5	VT	0.2049	−0.3005	−27.434	42.947	1454	26.919
	MT	0.0438	−0.2336	−10.942	42.801	3027.3	−726.24
	OMT	0.1226	−0.3104	−21.602	52.852	3007.1	−624.81
RCP8.5	VT	−0.1787	−0.0175	−23.212	46.138	1434.2	41.834
	MT	−0.2466	0.1224	−3.3338	45.077	2972.5	−698.86
	OMT	−0.2454	0.0578	−17.96	60.936	2978.3	−629.34

Table A3. Parameters used in Equation (4) for different climate change (cc) scenarios on Vtkg, Ptkg, Mtkg, and Rtkg drained peatland sites with fertility comparable to that of poor (dry heath, *Calluna* type, CT), quite poor (dryish heath, *Vaccinium* type, VT), medium (fresh heath, *Myrtillus* type, MT), and rich (grove-like heath, *Oxalis-Myrtillus* type, OMaT) upland sites (see Table A1).

Climate Scenario	Scots Pine	a2		b2		c2	
		p1	p	p3	p4	p5	p6
RCP2.6	Vtkg	0.1109	−0.195	−13.851	22.822	1145.9	−33.75
	Ptkg	0.1417	−0.2385	−17.551	27.937	1353.1	−10.743
	Mtkg	0.486	−0.6642	−53.049	71.784	2267.0	−738.19
	Rtkg	0.1882	−0.3093	−23.175	36.123	1675.7	56.96
RCP4.5	Vtkg	0.0542	−0.1454	−17.659	30.171	1165.98	−69.741
	Ptkg	0.0665	−0.174	−21.638	36.227	1373	−48.409
	Mtkg	0.0898	−0.2186	−27.229	44.667	1637.4	4.5115
	Rtkg	0.1029	−0.2349	−29.236	47.176	1706.8	5.4396
RCP8.5	Vtkg	−0.4773	0.2522	−6.2268	28.014	1101.9	−44.556
	Ptkg	−0.5411	0.2784	−9.1908	34.319	1289.9	−5.4983
	Mtkg	−0.6224	0.3045	−13.498	43.639	1546.3	45.133
	Rtkg	−0.6305	0.3026	−15.122	46.168	1618.1	43.917

Climate Scenario	Norway Spruce	a2		b2		c2	
		p1	p	p3	p4	p5	p6
RCP2.6	Ptkg	0.2154	−0.246	−24.896	27.520	297.05	931.75
	Mtkg	0.2664	−0.3009	−31.093	34.019	342.25	1191.2
	Rtkg	0.2781	−0.313	−32.575	35.547	358.45	1244
RCP4.5	Ptkg	0.1087	−0.1709	−30.345	34.976	317.08	901.57
	Mtkg	0.1385	−0.2107	−37.896	43.066	361.99	1164.8
	Rtkg	0.1484	−0.2239	−39.709	45.099	372.15	1222.7
RCP8.5	Ptkg	0.275	−0.4878	−67.374	75.415	578.19	644.41
	Mtkg	0.3454	−0.6047	−82.853	92.279	678.55	850.15
	Rtkg	0.363	−0.6333	−86.357	96.137	689.82	908.87

Climate Scenario	Silver Birch	a2		b2		c2	
		p1	p	p3	p4	p5	p6
RCP2.6	Ptkg	0.0434	−0.233	−6.1696	27.084	2641.4	−734.31
	Mtkg	0.0613	−0.2813	−8.3825	32.581	3025.7	−696.46
	Rtkg	0.0884	−0.3097	−3.4689	26.176	3078.8	−667.69
RCP4.5	Ptkg	0.0146	−0.1772	−5.5852	33.239	2616.4	−732.28
	Mtkg	0.0385	−0.2291	−10.035	42.041	3026.7	−725.84
	Rtkg	0.0696	−0.2611	−15.363	47.467	3092.7	−709.96
RCP8.5	Ptkg	−0.1475	0.0763	−0.7576	35.968	2564.9	−701.58
	Mtkg	0.155	0.0464	−5.6332	46.752	2986.8	−709.24
	Rtkg	−0.256	0.1162	−9.1187	51.45	3050.5	−697.06

Table A4. Mean growth change (% of that under the current temperature sum) in Scots pine, Norway spruce, and birch, and across all tree species, for all upland forest sites (NFI11 plots, see Table 2) for the current temperature sum (TS) regions, under mild (RCP2.6), moderate (RCP4.5), and severe (RCP8.5) climate change scenarios, for each calculation period between 2010 and 2099. The numbers in parentheses indicate the standard deviation of growth change.

TS Region	RCP2.6, Mean Growth Change (%)			RCP4.5, Mean Growth Change (%)			RCP8.5, Mean Growth Change (%)		
	2010–2039	2040–2069	2070–2099	2010–2039	2040–2069	2070–2099	2010–2039	2040–2069	2070–2099
Scots Pine									
Southern boreal, TS > 1200 d.d.	2.0 (1.1)	5.4 (3.1)	4.0 (3.1)	3.2 (1.6)	8.4 (5.0)	5.6 (6.1)	7.2 (2.5)	5.9 (9.3)	−38.7 (14.8)
Central boreal, TS 1000–1200 d.d.	4.5 (1.2)	12.8 (3.5)	11.7 (3.6)	6.5 (1.7)	19.7 (5.7)	21.6 (7.6)	11.2 (2.5)	23.0 (10.3)	−6.0 (18.2)
Northern boreal, TS < 1000 d.d.	9.7 (2.9)	28.4 (8.7)	27.8 (14.1)	13.6 (4.0)	44.0 (13.8)	55.0 (19.2)	20.3 (5.2)	61.4 (22.5)	65.3 (43.1)
Across the whole boreal region	5.2 (3.3)	15.1 (9.9)	14.1 (10.3)	7.5 (4.6)	23.3 (15.5)	26.4 (21.4)	12.6 (5.9)	28.9 (24.8)	4.7 (46.3)
Norway Spruce									
Southern boreal, TS > 1200 d.d.	−3.7 (1.2)	−11.8 (3.5)	−13.9 (3.2)	−4.4 (1.6)	−18.7 (5.0)	−35.2 (6.1)	−11.2 (2.8)	−52.8 (8.2)	−99.6 (1.1)
Central boreal, TS 1000–1200 d.d.	−1.0 (1.3)	−3.7 (3.8)	−5.5 (3.7)	−0.8 (1.8)	−6.1 (5.9)	−16.7 (7.7)	−3.7 (3.3)	−27.4 (10.6)	−74.6 (13.3)
Northern boreal, TS < 1000 d.d.	3.7 (2.3)	10.5 (6.8)	9.2 (7.0)	5.5 (3.1)	16.1 (11.0)	15.5 (15.8)	9.4 (6.4)	17.1 (21.9)	−13.6 (30.2)
Across the whole boreal region	−1.0 (3.1)	−3.6 (9.1)	−5.4 (9.3)	−0.8 (4.1)	−6.0 (14.2)	−16.6 (20.3)	−3.7 (8.3)	−27.2 (28.0)	−71.0 (34.7)
Silver Birch									
Southern boreal, TS > 1200 d.d.	5.6 (1.0)	16.4 (3.0)	16.2 (2.9)	8.0 (1.5)	26.7 (4.7)	35.6 (5.9)	11.8 (1.9)	39.3 (9.2)	52.2 (20.1)
Central boreal, TS 1000–1200 d.d.	7.4 (1.1)	22.0 (3.2)	21.9 (3.1)	10.5 (1.5)	35.3 (5.1)	47.2 (6.9)	15.0 (2.0)	52.4 (9.8)	75.2 (21.5)
Northern boreal, TS < 1000 d.d.	11.0 (2.0)	32.6 (6.0)	33.0 (6.1)	15.4 (2.9)	51.7 (10.0)	69.5 (14.0)	21.1 (3.7)	77.1 (17.7)	119.4 (37.4)
Across the whole boreal region	6.8 (2.0)	20.2 (5.8)	20.1 (6.0)	9.7 (2.7)	32.5 (9.2)	43.5 (12.3)	14.0 (3.5)	48.1 (15.3)	67.8 (30.0)

Table A5. Abbreviations.

Abbreviation	Meaning
a	Location-specific parameter
a2	Location-specific variable
b	Location-specific parameter
b2	Location-specific variable
c	Location-specific parameter
c2	Location-specific variable
cc	Climate change scenario
CMIP3 [1]	Coupled Model Intercomparison Project Phase 3, see footnote 1
CMIP5 [1]	Coupled Model Intercomparison Project Phase 5, see footnote 1
CO_2	Carbon dioxide
CT	*Calluna* type, dry heath
cur	Current climate
d.d.	Degree days, +5 °C threshold
DBH	Diameter (cm)
DBHm	Multiplier for diameter growth
FinnFor	FINNish FORest ecosystem model
g	Parameter
h	Parameter
K	Parameter for the relative diameter growth
KED	Kriging with external drift method
M_L	Multiplier in relation to the prevailing light conditions (from 0 to 1)
M_N	Multiplier in relation to the nitrogen supply (from 0 to 1)

Table A5. *Cont.*

Abbreviation	Meaning
Motti	Empirical growth and yield model at the Natural Resources Institute Finland
MT	*Myrtillus* type, fresh heath
Mtkg	Drained peatland site corresponding to *Myrtillus* type
M_{Ts}	Multiplier in relation to the temperature sum (from 0 to 1)
M_W	Multiplier in relation to the soil moisture (from 0 to 1)
N	Nitrogen
NFI11	The 11th National Forest Inventory
OMaT	*Oxalis-Maianthemum* type, rich grove-like heath
OMT	*Oxalis-Myrtillus* type, grove-like heath
p1 . . . p6	Parameters
ppm	Parts per million
Ptkg	Drained peatland site corresponding to *Vaccinium* type
q	Parameter for the relative diameter growth
RCP	Representative concentration pathway
RCP2.6 [2]	Mild climate change, see footnote 2
RCP4.5 [2]	Moderate climate change, see footnote 2
RCP8.5 [2]	Severe climate change, see footnote 2
Rtkg	Drained peatland site corresponding to *Calluna* type
SIMA	Gap-type forest ecosystem model, Metsän SImulointiMAlli
SRES [3]	Special Report on Emissions Scenarios, see footnote 3
SRES A1B [4]	Special Report on Emissions Scenario, see footnote 4
t	Year
TS	Temperature sum in degree days, +5 °C threshold (d.d.)
TS_{max}	Maximum temperature sum
TS_{min}	Minimum temperature sum
TS_{opt}	Temperature sum for maximum growth
VT	*Vaccinium* type, dryish heath
Vtkg	Drained peatland site corresponding to *Vaccinium* type
ΔDBH	Diameter growth (cm)
ΔDBH_o	Maximum diameter growth (cm)
ΔDBH_{rel}	Relative diameter growth
ΔP	Average change in precipitation (%)
ΔT	Average change in temperature (C°)

[1] **CMIP3, CMIP5:** Estimates for future climatic changes are based on simulations performed with global climate models (GCMs). To enhance the robustness of the estimates and to enable credible uncertainty analyses, one has to examine a sufficiently wide set of models. For that purpose, international data archives have been constructed. Climate scientists can download output data from a large set of models from these archives. The data banks of the Coupled Model Intercomparison Project (CMIP) have had a major role as the climate model data repository. The CMIP archives are updated in phase with the publication of the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). CMIP3 models contributed to the IPCC [64] report and the CMIP5 model ensemble was used in the IPCC [65] report; [2] **RCP2.6, RCP4.5, RCP8.5:** Representative Concentration Pathways (RCPs) refer to the total radiative forcing (in Wm^{-2}) near the year 2100. The philosophy behind the RCP forcing scenarios is explained in detail in [66]. Under the RCP2.6 scenario, the CO_2 concentrations start to diminish after mid-century. Under the RCP4.5 scenario, the CO_2 concentration stabilizes close to 540 ppm. Under the RCP8.5 scenario, emissions continue to increase throughout the 21st century and nearly three-fold compared to the level that prevailed in 2000. By 2100, the concentration of CO_2 would approach 1000 ppm; [3] **SRES:** Acronym SRES comes from the words Special Report on Emissions Scenarios (SRES), which was a report published by the Intergovernmental Panel on Climate Change (IPCC) in 2000. These scenarios have been used to project future atmospheric Greenhouse Gas (GHG) concentrations. The SRES scenarios [67] were used in IPCC's third and fourth assessment reports, published in 2003 and 2007, respectively; [4] **SRES A1B:** Under the A1B scenario, the world is characterized by very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technology. By 2100, the concentration of CO2 would approach 700 ppm.

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