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Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management

Seppo Kellomäki[1,*], Heli Peltola[1], Tuula Nuutinen[2], Kari T. Korhonen[2] and Harri Strandman[1]

[1]*Faculty of Forestry, University of Joensuu, PO Box 111, 80101 Joensuu, Finland*
[2]*Joensuu Research Unit, Finnish Forest Research Institute, PO Box 68, 80101 Joensuu, Finland*

This study investigated the sensitivity of managed boreal forests to climate change, with consequent needs to adapt the management to climate change. Model simulations representing the Finnish territory between 60 and 70° N showed that climate change may substantially change the dynamics of managed boreal forests in northern Europe. This is especially probable at the northern and southern edges of this forest zone. In the north, forest growth may increase, but the special features of northern forests may be diminished. In the south, climate change may create a suboptimal environment for Norway spruce. Dominance of Scots pine may increase on less fertile sites currently occupied by Norway spruce. Birches may compete with Scots pine even in these sites and the dominance of birches may increase. These changes may reduce the total forest growth locally but, over the whole of Finland, total forest growth may increase by 44%, with an increase of 82% in the potential cutting drain. The choice of appropriate species and reduced rotation length may sustain the productivity of forest land under climate change.

Keywords: adaptive management; boreal forest; timber production; Scots pine; Norway spruce; birch

1. INTRODUCTION

The Arctic Climate Impact Assessment (ACIA 2005, pp. 99–150) showed that climate change may profoundly change the functioning and the structure of the boreal forests. The main part of the circumpolar boreal forests is natural, but in Scandinavia (Finland, Norway and Sweden) they are intensively managed for timber production. Under these conditions, temperature may increase by 1–2°C in summer and by 2–3°C in winter over the next 50 years (Carter *et al.* 2005). Longer and warmer growing seasons may increase primary production (Bergh *et al.* 2003), which may be further increased by the enhanced decomposition of soil organic matter (SOM; Reich & Schlesinger 1992; Kirschbaum 1994; Lloyd & Taylor 1994) and the consequent increase in nutrient availability (Melillo *et al.* 1993). In general, higher temperatures and concurrent elevation in atmospheric CO_2 may increase growth in the Scandinavian boreal forests, wherever availability of soil moisture is high enough (Bergh *et al.* 2005).

The production of ecosystem services such as timber is linked to the successional process of the forest ecosystem. In management, the successional process is directed to produce such ecosystem structures that facilitate the production of the targeted services (e.g. timber production). Until now, only a few studies have analysed the impacts of climate change on managed forests (Kellomäki & Kolström 1993, 1994; Lasch *et al.* 2002, 2005), even though the majority of the European forests, for example, are regularly used and managed. Climate change impacts on the European forests and forestry have recently been reviewed in the Intergovernmental Panel on Climate Change (IPCC) process (Parry 2000). The report suggested that there is a clear need to modify the current management to accommodate climate change in different regions, including Finland (also cf. Kellomäki *et al.* 2005).

Forest ecosystems may adapt autonomously to climate change, but in managed forests it is important to influence the direction and the timing of adaptation processes in order to realize the management goals (IPCC 2001, p. 90). Management efforts are much affected by the residual or net impacts and are not avoided through autonomous adaptation. Needs of adaptive management are much affected by the sensitivity of forest growth to changes in climatic and edaphic properties of forest sites (cf. Lindner 2000; Lasch *et al.* 2002, 2005). Choice of suitable tree species may be among the key actions in adapting management to climate change, as outlined by Spittlehouse & Stewart (2003).

The aim of this study was to investigate the sensitivity of managed boreal forests to climate change, with consequent needs to adapt the management to climate change. The model-based analysis extended over the whole territory of Finland between 60 and 70° N and 20 and 32° E in northern Europe, and it used ground-truthed inventory data representing Scots pine

* Author for correspondence (seppo.kellomaki@joensuu.fi).

One contribution of 12 to a Theme Issue 'The boreal forest and global change'.

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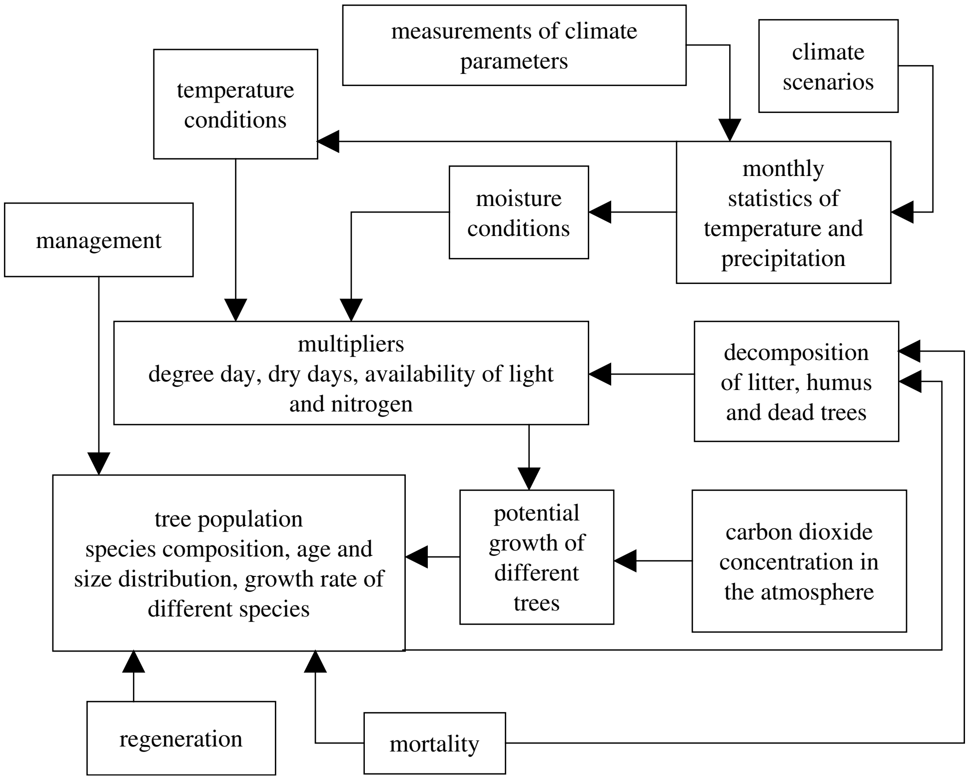

Figure 1. Outline of the model used in the simulations.

(*Pinus sylvestris*), Norway spruce (*Picea abies*), silver birch (*Betula pendula*) and downy birch (*Betula pubescens*) on sites of varying fertility. Potential timber and carbon sequestration were the main ecosystem services to be considered. In this context, only the climate risks related to changes in tree growth were assessed, excluding direct and indirect abiotic (e.g. wind and frost damage) and biotic (e.g. insect and fungus attacks) risks.

2. MATERIAL AND METHODS

(a) *Outline of the model*

The study used a forest ecosystem model which incorporates four environmental subroutines describing the site conditions that affect the growth and the development of forests, i.e. temperature, light, moisture and availability of nitrogen. These factors affect the demographic processes (birth, growth and death) in tree populations and communities (figure 1). The model structure and parametrization are described in detail by Kellomäki *et al.* (1992*a*,*b*) and Kolström (1998) for Scots pine, Norway spruce and birch. Therefore, only an outline of the model and its performance are described here.

Temperature controls the geographical limits and annual growth response of the species and their ecotypes included in the study. At the same time, competition for light controls tree growth as specific to the tree species and their height distributions. The effect of soil moisture is introduced in the model through the number of dry days, which indicates the number of days per growing season with soil moisture equal to or less than that at the wilting point specific for soil types and tree species. Soil moisture indicates the balance between precipitation, evaporation and drainage. Nitrogen availability is controlled by decomposition of litter and SOM as affected by the quality of litter and SOM and evapotranspiration.

Environmental conditions are linked by multipliers to the demographic processes, i.e. $G = G_o \cdot M_1, \ldots, M_n$, where G is growth and/or regeneration; G_o is growth and/or regeneration in optimal conditions; and $M_1, \ldots, M_n$ are multipliers representing the temperature sum (TS; +5°C threshold), prevailing light conditions, soil moisture and nitrogen supply. Optimal conditions refer to growth and/or regeneration under no shading and no limitation of soil moisture and nitrogen supply. In the case of growth, the values of G_o were further assumed to be related to maturity of the tree (diameter of tree, D cm) and the prevailing atmospheric CO_2 (figure 2),

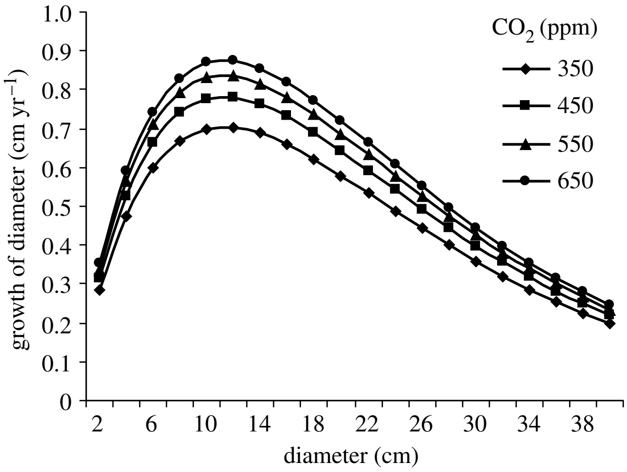

Figure 2. Example of the potential growth of Scots pine as a function of atmospheric CO_2 concentration and the breast height (1.3 m above ground level) diameter (diamond, 350; square, 450; triangle, 550; circle, 650).

$$G_o = \exp\left(-1.307 - \frac{1.643}{0.01 \times CO_2}\right) \times D \times e^{DGRO \times D}, \qquad (2.1)$$

where DGRO is a parameter with the value −0.0719 for Scots pine, −0.0562 for Norway spruce, −0.0706 for silver birch and −0.0917 for downy birch. The data for compiling function (2.1) were based on simulations of a physiological model applying the methodology presented by

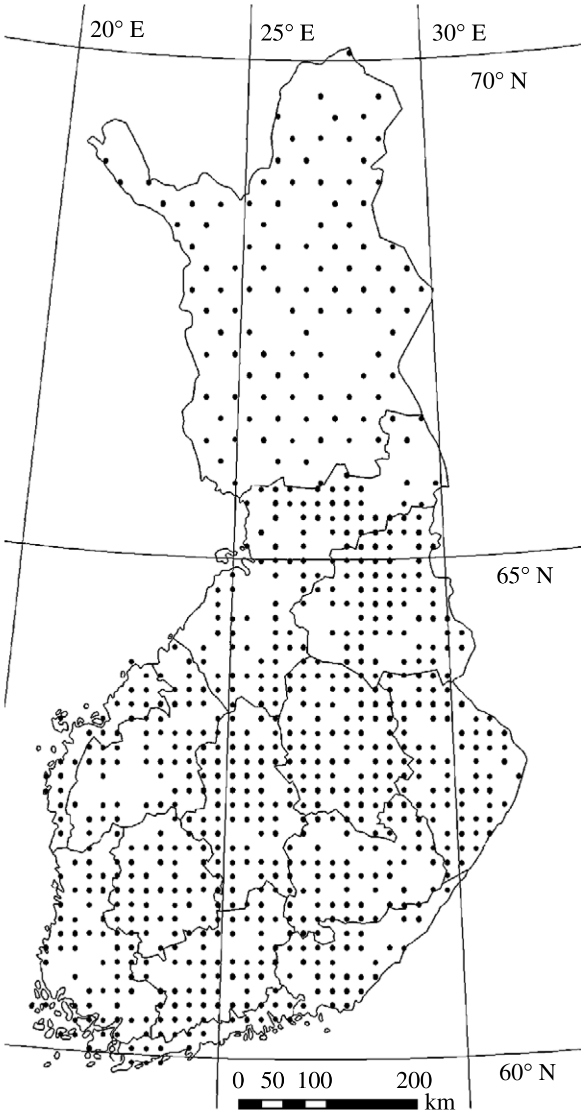

Figure 3. Grid of the permanent sample plots used in the Finnish National Forest Inventory.

Matala *et al.* (2005). In the simulations, the growth of single trees with ample supply of water and nitrogen was calculated under varying CO_2 concentration and no shading in the southern Finnish conditions.

Death of trees is determined by crowding with consequent reduction in growth and the probability of a particular tree dying at a given moment. Furthermore, trees die due to random reasons. Litter and dead trees end up on and in the soil, where they are decomposed with subsequent release of nitrogen bound in SOM.

Simulations are based on the Monte Carlo simulation technique, i.e. certain events, such as death of trees, are stochastic events. Each time such an event is possible (e.g. it is possible for a tree to die every year), the algorithm selects whether or not the event will take place by comparing a random number with the probability of occurrence of the event. The probability of an event is a function of the state of the forest ecosystem at the time when the event is possible. Each run of the code is one realization of all possible time courses of ecosystem development. Therefore, the simulations are repeated several times in order to determine the central tendency of variations in the time behaviour of the forest ecosystem. The model is run on an annual basis for areas of $100\,m^2$; these areas represent the permanent sample plots of the Finnish National Forest Inventory. For each sample plot, simulations were repeated 50 times.

Table 1. Values of field capacity and wilting point used to describe the water holding capacity of soil in the top 30 cm soil layer.

soil type	field capacity (mm)	wilting point (mm)
rough moraine	60	9
fine moraine	105	45
gravel	12	0
sand	15	3
fine sand	75	6
silt	120	30
clay	126	75

(b) *Input to model runs*

(i) *Sites*

The study covered 26 Mha of forest land represented by the permanent sample plots of the Finnish National Forest Inventory. The sample plots were established by the Finnish Forest Institute in 1985. The plots are located in blocks of four plots in the south and three in the north. The blocks form a $16\times16\,km^2$ grid in southern Finland and a $32\times32\,km^2$ grid in northern Finland (figure 2). Only plots on upland mineral soils were used. The measurements made in 1985 were used in calibrating the height growth model as regards the ecotypic differences over the country. In the proper simulations, measurements updated in 1995 were used in initializing the simulations.

The total number of plots was 1368. Most of them were located on sites of medium fertility or close to it, i.e. *Oxalis–Myrtillus* type (OMT, 256 sites), *Myrtillus* type (MT, 630 sites), *Vaccinium* type (VT, 361 sites) and *Calluna* type (CT, 121 sites). The dominant tree species on the *Oxalis-Maianthemum* type (OMaT) and OMT sites is Norway spruce with admixtures of birch, while the MT site type is often a mixture of Norway spruce, birch and Scots pine, and on VT, CT and *Cladonia* (ClT) site types, the main tree species is mostly Scots pine (figure 3).

The site type of the plots was used to define the soil type (Urvas & Erviö 1974), subdividing the classification of soils into rough moraine, fine moraine, gravel, sand, fine sand, silt and clay (Talkkari & Hypén 1996). Most of the plots (1006 out of 1256) were located on unsorted coarse and fine moraine soils. The most common soil textures among the sorted soils were sand and fine sand (177 out of 1256). Regarding the soil type, the values of field capacity and wilting points in table 1 were used in calculating the water-holding capacity of the soil in the plots down to 30 cm. For the tree species in this study, more than 90% of the total root mass is situated in this soil layer (Kalela 1949).

The amount of litter and humus (SOM) on the plots was defined on the basis of the thickness of the organic layer measured in the inventory. The thickness was converted into the mass of SOM, using the bulk density of SOM considering the site type and tree species dominating the plot (Tamminen 1991; Talkkari & Hypén 1996). Thereafter, the mass of SOM was regressed against the prevailing TS of the plot by the site types as presented in figure 4. These values were used in initializing the simulations for a specific plot. The values were further used in calculating the initial amount of nitrogen in soil, applying the values of the total nitrogen concentration of the humus layer by site type and tree species (Tamminen 1991).

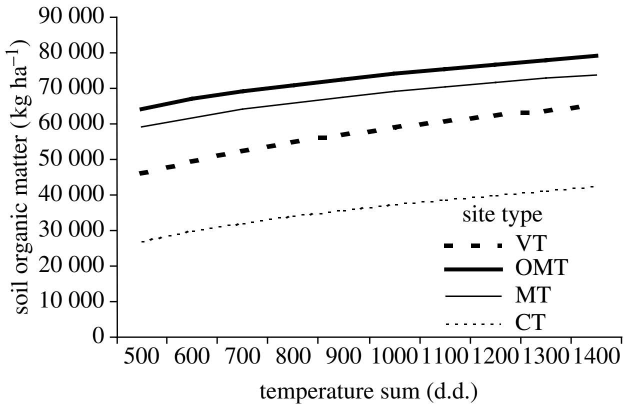

Figure 4. Mass of SOM as a function of site type and TS.

Table 2. Values of the parameters for the height model (equation (2.2)) by tree species estimated from the data of the Finnish National Forest Inventory updated in 1985.

tree species	*A*	*B*	*C*	R^2	*N*
Scots pine	2.117	0.166	0.435	0.848	4170
Norway spruce	2.137	0.159	0.669	0.918	3017
silver birch	1.669	0.169	0.730	0.885	340
downy birch	1.336	0.200	0.941	0.867	924

(ii) *Tree population*

For initializing the simulation, the properties of tree populations were described in terms of tree species with the number of trees per hectare in each diameter class. The diameter (*D*, cm at 1.3 m above soil surface) was used to calculate the mass of tree organs (foliage, branches, stem and roots) by applying allometric equations with species-specific parameter values (Kolström 1998). The diameter was also used in calculating the tree height (*H*, m) by applying the height model of Näslund (1936), modified by including the current TS of the sample plots,

$$H = \left[\frac{\mathrm{TS}}{1000}\right]^{C} \times \left[1.3 + \frac{D^2}{(A + B \times D)^2}\right], \tag{2.2}$$

where *A*, *B* and *C* are parameters (table 2). The current TS indicates the geographical location of the plot, i.e. the ecotype differences (provenances) in the growth responses of trees to the climate. An example in figure 5 shows that in the north a given diameter of Scots pine implies shorter trees than in the south, as one may expect on the basis of the provenance experiments (Beuker 1994; Beuker *et al.* 1996).

(c) *Management procedure*

The algorithm allows simulation of the management including nitrogen fertilization, thinning, terminal cut and regeneration. Fertilization directly affects the availability of nitrogen in the soil. The thinning rules followed those currently recommended for different tree species, site types and regions (separately for southern and northern Finland; Yrjölä 2002). Thinning was done from below and trees were removed from the population to such an extent that stocking was reduced to the expected value at a given phase of forest development. The final felling was executed whenever the mean diameter of trees on the plots exceeded the given value indicating the maturity as presented in table 3. The values defined by the upper limit were used in the simulations to indicate the time of the final felling.

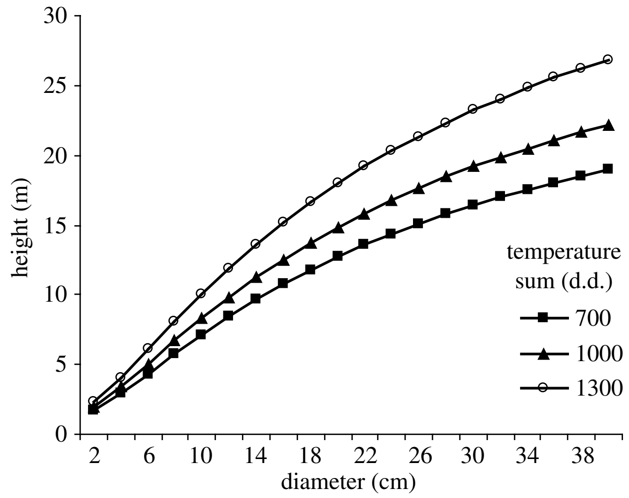

Figure 5. Performance of the height growth model for Scots pine as a function of diameter and prevailing TS (square, 700; triangle, 1000; circle, 1300) of the plots applying the parameter values of equation (2.2) in table 2.

Table 3. Mean diameter of tree populations ready for final felling as a function of tree species, site type and region used in simulations (Hyvän metsänhoidon suositukset 2001).

	mean diameter when ready for the final felling (cm)	
tree species and site type	southern Finland	northern Finland
Scots pine		
OMT, MT and more fertile	29–31	26–29
VT	27–29	24–27
CT and less fertile	25–27	23–25
Norway spruce		
OMT and more fertile	28–30	23–26
MT	26–28	
silver birch		
OMT and more fertile	28–30	23–26
MT	26–28	23–26
downy birch		
OMT, MT and more fertile	25–27	23–24

In practice, the management rules are only seldom applied systematically. This has led to increasing stocking due to cuttings that are less than growth (Metsätilastollinen vuosikirja 2004). This is the case, especially in southern Finland, where cuttings are clearly delayed compared with that indicated by the management rules. Consequently, straightforward simulations with the current management rules would have led to a too large cutting drain and a large reduction of stocking at the beginning of the simulation. Therefore, the deterministic application of management rules was replaced by a random procedure. Whenever the management rules indicated thinning or terminal cut for a tree stand, a random number *r* (0, …, 1) was selected, and its value compared to the value of the parameter *p*. If $r<p$, no cutting was executed. The value of $p=0.95$ was selected. This implies that the mean delay (*x*) for cutting is 13 years compared to that indicated by the management rules, i.e.

$$p^x = 0.5 \Rightarrow x = 13 \text{ years}. \tag{2.3}$$

This delay meant that there was no major change in stocking at the beginning of the simulation, with an implication that simulated cuttings were comparable to the business-as-usual management currently applied in Finland.

The terminal cut was done in the form of a clear cut, and the site was planted with the same tree species occupying the site before the terminal cut. The planting density was 2000 saplings ha^{-1} throughout the country, regardless of the tree species and site type. Invasion by other tree species was allowed on clear-cut areas, assuming natural regeneration from forests around the plots. Natural regeneration was simulated with the model built by Pukkala (1987), based on long-term seed crop inventories throughout Finland (Koski & Tallqvist 1978). These plants were added to the new tree population if the site quality was appropriate for the species. Scots pine seedlings were accepted over the whole range of site types. Norway spruce and birch were accepted only on fertile sites of *Myrtillus*, *Oxalis–Myrtillus* and *Oxalis–Maianthemum* types.

Trees removed in thinning and final cut were converted to saw logs and pulp wood. The concept of saw log refers to the butt part of the stem with a minimum diameter of 15 cm at the top of the log, while pulp wood refers to the other parts of the stem, with a minimum diameter of 6 cm; the rest of the stem represents logging residue. In calculating the amount of different timber assortments from the stem, empirical tables (V. Snellman, Finnish Forest Research Institute 1983, unpublished data) giving the amount of saw logs, pulp wood and logging residue as a function of the breast height diameter of the stem were used.

(iii) *Climate data*

The spatial resolution of the grid for the current climate (1961–1990) used in the reference simulations was $10\times10\ km^2$, and the resolution for the climate change scenarios was $49\times49\ km^2$ (Ruosteenoja *et al.* 2005; Venäläinen *et al.* 2005) as provided by the Finnish Meteorological Institute. In both cases, the climate data represented the daily values over seasons, introducing the inter-annual variability around the trend-like changes in the climate. Based on the daily values, the monthly mean temperature with standard deviation and the monthly mean precipitation with standard deviation were calculated over the periods applicable in the context of the model. In the simulations for a given sample plot, the calculation algorithm uses the climate in the closest grid point of the climate data.

In the reference simulations, the current climate was used over the period 1991–2099, applying a constant atmospheric concentration of CO_2 of 352 ppm. The climate change scenarios were given in three periods, 1991–2020, 2021–2050 and 2070–2099, based on the IPCC SRES A2 emission scenario (Ruosteenoja *et al.* 2005). In each period, the mean temperature and precipitation representing the midpoint of the period were used in the model. The values between the midpoints were based on a linear interpolation between the values at two consecutive midpoints. By 2070–2099, the mean temperatures are projected to increase almost 4°C in the summer and more than 6°C in the winter. The atmospheric concentration of CO_2 was 352 ppm at the start of simulations in 1990 and 841 ppm at the end of simulation in 2099.

(**d**) ***Performance of the model***

The model performance was analysed on the basis of growth of different tree species available for different Forest Centres provided by the National Forest Inventory (Metsätilastollinen vuosikirja 2004). Altogether, there are 13 Forest Centres (the administrative forest regions) in Finland. The growth values based in the inventory use more than 70 000 sample plots, which are allocated to the Forest Centres based on their share of the total forest area in Finland.

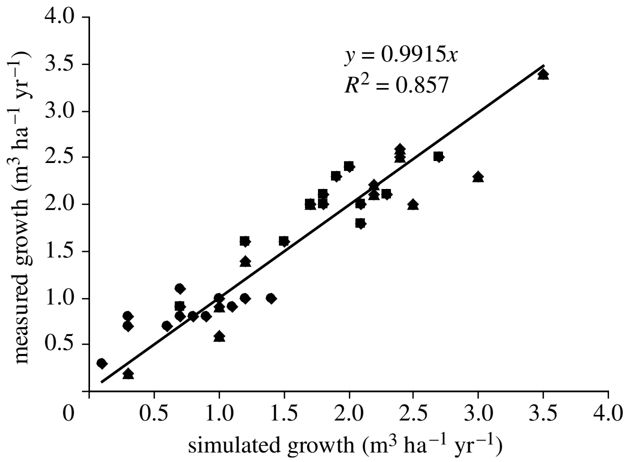

Figure 6. Simulated growth values of different tree species for different Forest Centres against the values provided by the National Forest Inventory (Metsätilastollinen vuosikirja 2004) (filled square, pine, filled triangle, spruce, filled circle, birch).

The same growth values were calculated with the model based on the permanent sample plots located in the territory of a given Forest Centre. The calculations used the height growth model, the parameters of which were estimated on the basis of the first measurements of the sample plots in 1985 in order to calibrate the height growth model to the ecotypic differences in height growth between southern and northern Finland (see table 2; figure 5). Values of other parameters were estimated from other data (Kellomäki *et al.* 1992*a*,*b*; Kolström 1998) than that used in the calculations. Figure 6 shows that there is a close correlation between the values provided by the National Forest Inventory for different Forest Centres by species and the simulated values.

3. RESULTS

(**a**) ***Impacts on growth***

Figure 7 shows that the growth integrated over tree species varies currently from less than 1 $m^3\ ha^{-1}\ yr^{-1}$ in the north to up to 6 $m^3\ ha^{-1}\ yr^{-1}$ in the south. Throughout northern Finland, growth increase was several tens of percentages under the changing climate. In southern Finland, the increase was much less, ranging mainly from 10 to 20%. The growth increase of Norway spruce was in many places (mainly south of latitude 62° N) very small or even negative, especially during the latter phase of the simulation period. This was due to the increase in the occurrence of drought periods along with the temperature increase (figure 8). It is probable that Norway spruce may be successful only on fertile and moist sites (e.g. sites of OMT), where water supply is sufficient even under longer drought periods. In these conditions, Norway spruce is probably competitive with birch and other deciduous species, even though the dominance of birch increased on the fertile sites. On the other hand, the dominance of Scots pine increased on less fertile sites currently occupied by Norway spruce, e.g. on the sites of MT.

Changes in growth and tree species composition caused local reductions in total growth, but on a national scale total growth may increase (table 4). This is mainly due to the growth increase of all the species in northern Finland and the growth increase of Scots pine

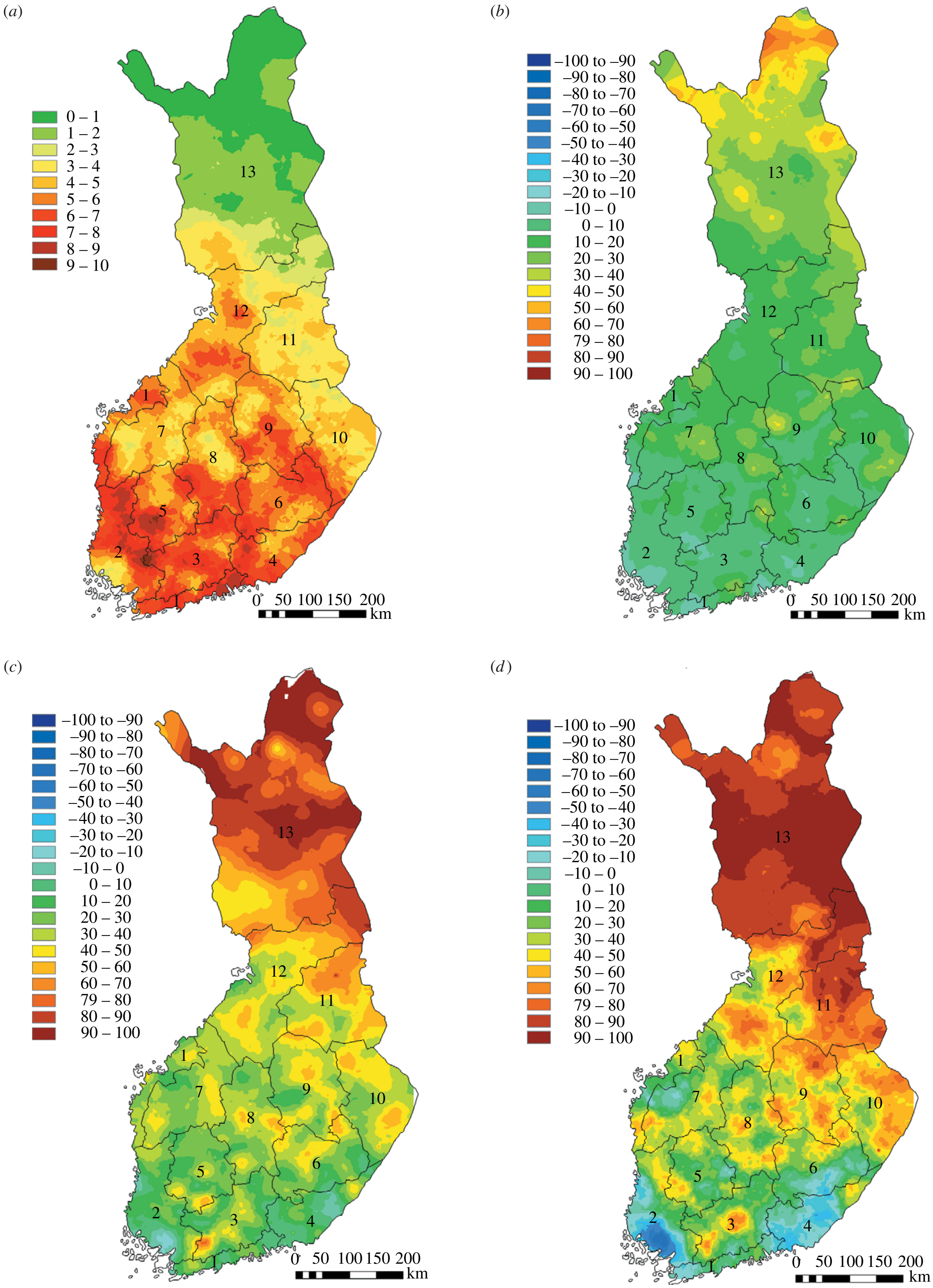

Figure 7. Integrated growth of all tree species under the current climate, and the change in growth under climate change: (*a*) total current growth ($m^3\ ha^{-1}\ yr^{-1}$); percentage of total growth change for (*b*) 1991–2020, (*c*) 2021–2050 and (*d*) 2070–2099. The numbers on the maps refer to the Finnish Forest Centres.

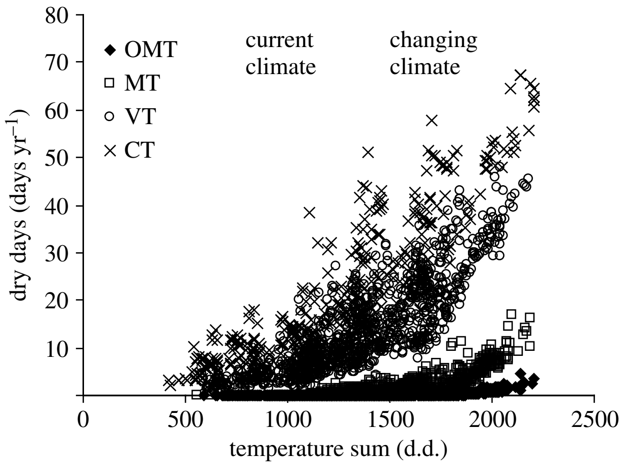

Figure 8. Number of dry days as a function of TS and site type under the current climate and changing climate. A dry day is a day when the soil moisture is below the wilting point specific for each soil type given in table 1.

Table 4. Mean growth of forests currently and in different time slices under climate change divided between southern and northern Finland. (Northern Finland includes the regions 11–13 above approx. 63° N and southern Finland includes the regions 1–10 below approx. 63° N (see figure 7). The values in parentheses are the percentage change.)

region	growth ($m^3\ ha^{-1}\ yr^{-1}$)			
	current	1990–2020	2021–2050	2050–2099
southern Finland	5.5	5.9 (7%)	6.3 (11%)	6.8 (12%)
northern Finland	2.2	2.6 (18%)	3.7 (68%)	4.6 (109%)
total	4.1	4.5 (10%)	5.3 (29%)	5.9 (44%)

Table 5. Mean total stocking of trees in different time slices under climate change divided between southern and northern Finland. (Northern Finland includes the regions 11–13 above approximately 63° N, and southern Finland includes the regions 1–10 below approximately 63° N. The values in parentheses are the percentage change.)

region	total stocking ($m^3\ ha^{-1}$)			
	current	1990–2020	2021–2050	2050–2099
southern Finland	144	146 (1%)	173 (20%)	144 (0%)
northern Finland	78	82 (5%)	125 (59%)	145 (86%)
total	117	120 (2%)	154 (31%)	144 (23%)

Table 6. Tree species composition in per cent of the total stocking in different time slices divided between southern and northern Finland. (Northern Finland includes the regions 11–13 above approximately 63° N, and southern Finland the regions 1–10 below approximately 63° N.)

region and species	current	1991–2020	2021–2050	2070–2099
southern Finland				
Scots pine (%)	42	44	54	62
Norway spruce (%)	49	45	33	8
birch (%)	9	11	13	30
northern Finland				
Scots pine (%)	62	63	68	77
Norway spruce (%)	27	26	22	14
birch (%)	11	11	10	8
total				
Scots pine (%)	47	49	59	68
Norway spruce (%)	43	39	29	12
birch (%)	10	12	12	20

throughout southern and central Finland. The southwestern and southeastern corners of the country are exceptional, where Scots pine currently occupies mainly poor sites. In such conditions, the increased occurrence of drought periods may reduce the growth of even Scots pine.

(b) *Impacts on stocking*

Currently, the stocking in southern Finland goes up to 180 $m^3\ ha^{-1}$, the highest values representing the southwestern parts of the country. In northern Finland, the stocking goes up to 100 $m^3\ ha^{-1}$ at the maximum, but in large areas the values are much less. Under climate change, most increase may occur in northern Finland as can be expected on the basis of changes in growth. In southern Finland, the stocking may also increase, except in the southwestern and southeastern parts of the country, where reduction in growth of Norway spruce leads to a reduction in stocking. Table 5 shows that, in the latter part of the simulation period, mean stocking in southern Finland may be 144 $m^3\ ha^{-1}$ and in northern Finland 145 $m^3\ ha^{-1}$. Mean stocking in southern Finland remained fairly stable, but in northern Finland it was double that of the current situation.

(c) *Impacts on tree species composition*

The share of Scots pine in southern Finland may increase up to 60% of the total volume by the latter part of the simulation period (table 6). At the same time, the share of Norway spruce may decrease down to 10%. Most of the reduction occurs during the latter part of the simulation period when birch seems to replace Norway spruce in many places. In northern Finland too, the share of Norway spruce may decrease, but now Norway spruce is replaced by Scots pine, whose share exceeds 70% of the total stem wood volume. In northern Finland, the share of birch seems to remain quite stable or may even slightly decrease in comparison with the current situation.

(d) *Impacts on potential cutting drain*

In southern Finland, the potential cutting drains (i.e. maximum sustainable removals under a given management) may increase by up to 56% by the end of the simulation period (table 7). In northern Finland, the increase is much larger (up to 170%), but there the absolute value (3 $m^3\ ha^{-1}\ yr^{-1}$) is still less than two-thirds of that in southern Finland (5 $m^3\ ha^{-1}\ yr^{-1}$).

The total potential cutting drain over the whole of the country increased (table 8). Note that the potential

Table 7. Potential cutting drains currently and in different time slices under climate change divided between southern and northern Finland. (Northern Finland includes the regions 11–13 above approximately 63° N, and southern Finland the regions 1–10 below approximately 63° N. The values in parentheses are the percentage change.)

region	potential cutting drains ($m^3\ ha^{-1}\ yr^{-1}$)			
	current	1990–2020	2021–2050	2050–2099
southern Finland	3.2	3.3 (3%)	4.2 (31%)	5.0 (56%)
northern Finland	1.1	1.2 (9%)	2.2 (100%)	3.0 (168%)
total	2.3	2.4 (4%)	3.3 (52%)	4.2 (82%)

cutting drains represent only upland sites on mineral soils excluding peatlands. Partly for this reason, values for the current climate are 85% of that presented in the forestry statistics, e.g. 56 $Mm^3\ yr^{-1}$ for 2003 (Metsätilastollinen vuosikirja 2004). Furthermore, the distribution of timber assortments changed, i.e. in southern Finland, the share of saw logs increased from 77% at the beginning of the simulation to 82% at the end of the simulation, and in northern Finland from 74 to 82%, respectively.

(e) *Impacts on carbon sequestration*

Carbon in the forest ecosystems follows currently the same pattern as growth and stocking, i.e. in southern Finland the total amount of carbon is 100 $Mg\ ha^{-1}$ over larger areas, whereas in northern Finland the amount of total carbon remains 50 $Mg\ ha^{-1}$ (table 9). Under climate change, the amount of carbon increases more in the north than in the south as one may expect on the basis of changes in growth. However, the mean total amount of carbon remains somewhat smaller in the north than in the south, where the total amount of carbon may decrease in the areas with the largest reduction of growth and stocking of Norway spruce. Over the whole country, the total amount of ecosystem carbon is close to 30% greater than current amounts.

(f) *Management to adapt forests to climate change*

The simulations showed that productivity of the forest ecosystems may be reduced because climate change may create a suboptimal environment for Norway spruce in some areas. Obviously, there are two main tasks in adapting to climate change, i.e. to maintain (i) the current productivity of the forest ecosystems and especially (ii) the growth of Norway spruce. Three basic strategies were applied in reformulating the current management to meet the changes in climate.

First, the length of the rotation was reduced by making the terminal cut when the minimum value of the mean diameter of trees, indicating the maturity for regeneration, was exceeded, instead of making the terminal cut when the maximum mean diameter was exceeded. Second, Norway spruce was replaced by Scots pine or birch on sites of MT, and Norway spruce was preferred for planting only on the sites with higher fertility, if this species was occupying the site prior to the terminal cut. Third, a more southern provenance of Norway spruce was used in planting. The new provenance was described by changing the maximum and minimum TS in the TS multiplier of the growth model for Norway spruce. This changed the maximum value from 2060 to 2500 degree days (d.d.) and the minimum values from 170 to 360 d.d.

Table 8. Potential total cutting drains currently and in different time slices under climate change divided between southern and northern Finland. (Northern Finland includes the regions 11–13 above approximately 63° N, and southern Finland includes the regions 1–10 below approximately 63° N. Note that the potential cutting drains represent only the upland sites on mineral soils excluding peatlands.)

region	potential total cutting drains ($Mm^3\ yr^{-1}$)			
	current	1990–2020	2021–2050	2051–2099
southern Finland	36	37	47	56
northern Finland	10	11	20	27
total	46	48	67	83

The reduction of rotation length reduced growth of Norway spruce (up to 16%), but increased total growth (up to 28%) because growth of Scots pine and birch increased (table 10). The increase was largest in the south where total growth increased up to 35%. This was much more than that obtained when preferring Scots pine on sites of MT (12%), i.e. increased growth of Scots pine was not able to compensate for the reduction in growth of Norway spruce and birch. Total growth increased mostly (38%) in the case where birch was preferred on sites of MT. Use of the more southern ecotype of Norway spruce also increased the total growth (31%).

4. DISCUSSION AND CONCLUSIONS

Model simulations were applied to study how elevating atmospheric CO_2 and climate change in terms of temperature and precipitation may affect growth and timber yield throughout the Finnish territory representing boreal conditions. More than 90% of these forests are under regular management, including clear cuts with regeneration by planting and regular thinnings. Management disturbances substantially modify the natural dynamics of these forests, which may further be disturbed by the elevation of atmospheric CO_2 and changes in temperature and precipitation. Both types of disturbances were integrated in the simulations in order to analyse future timber production potentials and to identify risks that climate change may induce for sustainable forest management. In this respect, only the climate risks related to changes in tree growth were assessed, excluding direct and indirect abiotic (e.g. wind and frost damage) and biotic (e.g. insect and fungus attack) risks, because these risks can be assessed only qualitatively, with many problems incorporating them into growth and yield models.

Previously, Talkkari & Hypén (1996) had extended similar simulations over the whole of Finland, but they did not consider the effects of CO_2 in their calculations.

Table 9. Amount of carbon in forest ecosystem currently and in different time slices divided between southern and northern Finland. (Northern Finland includes the regions 11–13 above approximately 63° N, and southern Finland includes the regions 1–10 below approximately 63° N. The values in parentheses are the percentage change.)

	carbon (Mg ha^{-1})			
region	current	1991–2020	2021–2050	2070–2099
trees				
southern Finland	49	52 (5.9%)	57 (17.1%)	53 (8.3%)
northern Finland	25	28 (11.9%)	36 (45.8%)	40 (60.8%)
total mean	39	42 (8.3%)	50 (28.8%)	51 (29.7%)
soil				
southern Finland	40	40 (0.1%)	43 (7.2%)	50 (23.9%)
northern Finland	32	32 (0%)	34 (6.1%)	41 (28.4%)
total mean	37	37 (0%)	39 (6.8%)	46 (25.7%)
trees and soil				
southern Finland	89	90 (1.5%)	100 (12.6%)	102 (14.7%)
northern Finland	57	58 (2.2%)	70 (23.0%)	82 (45.3%)
total mean	76	77 (1.8%)	89 (16.8%)	96 (27.1%)

Table 10. Mean growth of different tree species in southern and northern Finland (2070–2099) under selected management regimes.

	growth (m^3 ha^{-1} yr^{-1}; % of that under current management rules)			
management regime	Scots pine	Norway spruce	birch	total
management with no modifications				
south	2.81	0.26	3.62	6.69
north	3.19	0.58	0.84	4.61
total	2.96	0.39	2.49	5.84
management with terminal cut, when the minimum diameter requirement is exceeded				
south	3.42 (+22)	0.24 (−8)	5.36 (+48)	9.02 (+35)
north	3.70 (+16)	0.49 (−16)	1.07 (+27)	5.26 (+14)
total	3.54 (+20)	0.34 (−13)	3.62 (+45)	7.50 (+28)
preferring Scots pine on Myrtillus *site if previously occupied by Norway spruce. Terminal cut at the minimum diameter requirement*				
south	4.06 (+44)	0.17 (−35)	3.29 (−9)	7.53 (+13)
north	3.99 (+25)	0.39 (−33)	0.70 (−17)	5.08 (+10)
total	4.03 (+36)	0.26 (−33)	2.24 (−10)	6.53 (+12)
preferring birch on Myrtillus *site if previously occupied by Norway spruce. Terminal cut at the minimum diameter requirement*				
south	3.12 (+11)	0.17 (−35)	6.79 (+88)	10.08 (+51)
north	3.53 (+11)	0.49 (−16)	1.14 (+36)	5.16 (+12)
total	3.29 (+11)	0.30 (−23)	4.49 (+80)	8.08 (+38)
preferring Norway spruce of more southern ecotype. Terminal cut at the minimum diameter requirement				
south	3.04 (+8)	0.67 (+158)	5.56 (+54)	9.27 (+39)
north	3.60 (+13)	0.44 (−24)	1.23 (+46)	5.27 (+14)
total	3.27 (+10)	0.57 (+46)	3.80 (+53)	7.64 (+31)

On the other hand, the previous calculations are limited to the scale of single stands (Kellomäki & Kolström 1993, 1994; Kellomäki & Väisänen 1997) with many problems in generalizing the findings to the national scale. The current calculations use also a new height growth model that includes ecotypic variability in height growth, neglected in the previous studies. This makes the calculation more realistic, especially for northern Finland. Furthermore, the regional management rules and random procedure in applying them make the simulations more realistic when mimicking the random component always associated with management decisions.

The simulations are based on the most recent climate scenarios scaled down to the same scale as the grid of the sample plots used in the calculations. This improves substantially the possibilities to apply site-specific climatic conditions compared to the previous calculations, in which the spatial scale of climate scenarios was hundreds of kilometres (Talkkari & Hypén 1996). However, this will not eliminate the uncertainties associated with the climate scenarios, which are especially large in the latter part of the simulation period (Ruosteenoja *et al.* 2005). During the first 30–40 years, different climate scenarios indicate quite consistently similar changes in future temperature and precipitation.

The simulations showed that the largest effects are experienced in the most northern and most southern parts of Finland. In the north, forest growth may increase substantially, but it will still be less than that currently in southern Finland. The simulations were done assuming concurrent elevation of temperature and CO_2 and changes in precipitation and not trying to identify separate impacts of these factors on tree growth. Nevertheless, Briceño-Elizondo *et al.* (2006*b*) have found that, in the north, growth increase is mainly related to elevation in temperature. In the south, direct temperature effects may be even smaller than that of elevation of CO_2, which may partly compensate the growth reduction due to increased drought episodes under temperature elevation (cf. Kellomäki & Väisänen 1997; Briceño-Elizondo *et al.* 2006*b*).

The above findings imply that the special features of northern forests may be diminished. This development is probably quite inevitable, and little can be done in order to conserve the present character of the northern forests. It may be necessary to adapt the management of northern forests to accommodate the higher productivity and changes in tree species composition that may characterize these forests in the future (cf. Briceño-Elizondo *et al.* 2006*a*,*b*). In southern Finland, climate change may create a suboptimal environment for Norway spruce as one may expect to occur in semi-continental conditions (Bergh *et al.* 2003; Lasch *et al.* 2005). It is probable that Norway spruce may survive only on the most fertile and moist upland sites (e.g. sites of OMT) with sufficient water supply even under longer drought periods. In these conditions, Norway spruce is probably competitive with birch and other deciduous species. On the other hand, the dominance of Scots pine may increase on less fertile sites currently occupied by Norway spruce (e.g. sites of MT). However, the growth of birch may compete with Scots pine even in these sites, and the dominance of birch may increase substantially. These changes only have negative effects on total growth of forests at the local scale, and at the national scale total growth may increase substantially. It seems that the choice of the most appropriate tree species is a basis for an adaptive management when aiming to maintain the productivity of forests under climate change (Badeck *et al.* 2005). Furthermore, reduced rotation length with more rapid turnover of forest resources may help to maintain productivity under climate change.

The simulations showed that in southern Finland the potential cutting drains may increase up to 56% by the end of the simulation period. In northern Finland, the increase is much larger (up to 170%), but there the absolute value ($3\ m^3\ ha^{-1}\ yr^{-1}$) is still less than two-thirds that in southern Finland ($5\ m^3\ ha^{-1}\ yr^{-1}$). The potential total cutting drain over the country may increase up to 82%. The increase in growth and timber resources imply that under climate change the amount of carbon in the forest ecosystem may increase throughout the country. However, the mean total amount of carbon remains somewhat smaller in the north than in the south, where the total amount of carbon may decrease in areas with the largest reduction of growth and stocking of Norway spruce. Over the whole country, the total amount of carbon in upland sites may be close to 30% greater than at present.

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