Impacts of climate change on forest growth: a modelling approach with application to management

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Academic dissertation

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ABSTRACT

The aim of this thesis was to modify and apply a statistical growth and yield model for analysing forest resources and optimal management under a changing climate in Finland. Initially, the structural and functional properties of physiological and statistical growth and yield models were compared under the current climate to assess whether the physiological model could be utilised in the modification of the statistical model (I). Thereafter, the impacts of elevated temperature and CO_2 on tree growth were introduced into a statistical growth and yield model with species-specific transfer functions, which were formulated based on data simulated with a physiological model (II-III). These functions were created separately for three main tree species and they described the increase in stem volume growth of trees as a function of elevated temperature and CO_2, stand density, competition status of a tree in a stand, geographical location and site fertility type of a stand. This method allowed the internal dynamics of the statistical model to be followed when the impacts of climate change were applied to the volume growth, allocated between diameter and height growth. Finally, this methodology was applied to derive an optimal management solution for a forest region located in eastern Finland under a changing climate by using the large-scale forestry scenario model and National Forest Inventory sample plot data (IV).

In model comparisons, it was found that the physiological and statistical models agreed well in terms of relative growth rates regardless of tree species (I). This implies that both models predicted in a similar way the competition within a stand and the effect of position on tree growth. However, the statistical model was less sensitive to initial stand conditions and management than the physiological model. The transfer functions worked reasonably well in the statistical model and the model predictions were logical as regards the differences in productivity between species, sites and locations under current and changing climate (II, III). In these simulations, the volume growth was enhanced less in southern than in northern Finland, where currently low summer temperatures are more limiting to growth. In a regional forestry scenario analyses (IV), the accelerating tree growth under a changing climate increased the maximum sustainable removal of timber at regional level. Changes in optimal forest management were also detected: the proportion of thinnings increased because the stands fulfilled thinning requirements earlier, and the optimisation allocated more cuttings on mineral soils where extraction of wood was cheaper than on peatlands.

Altogether, this study presents an attempt to integrate the capabilities of physiological and statistical growth and yield modelling approaches in order to make the latter more responsive to changing environmental conditions. As a result, the statistical model system can be expected to provide more precise predictions for a regional forestry scenario analyses by solving endogenously optimal forest management under a changing climate in boreal conditions.

Keywords: boreal forest, physiological model, statistical model, yield, model linking, forestry scenario analysis

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Joensuu, September 2005

Juho Matala

LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following papers referred to in the text by the Roman numerals I-IV:

I Matala, J., Hynynen, J., Miina, J., Ojansuu.R., Peltola, H., Sievänen, R., Väisänen, H. and Kellomäki, S. 2003. Comparison of a physiological model and a statistical model for prediction of growth and yield in boreal forests. Ecological Modelling 161: 95-116. doi:10.1016/S0304-3800(02)00297-1

II Matala, J., Ojansuu, R., Peltola H., Sievänen, R. and Kellomäki, S. 2005. Introducing effects of temperature and CO_2 elevation on tree growth into a statistical growth and yield model. Ecological Modelling 181: 173-190. doi:10.1016/j.ecolmodel.2004.06.030

III Matala, J., Ojansuu, R., Peltola, H., Raitio, H. and Kellomäki, S. 2005. Modelling the response of tree growth to temperature and CO_2 elevation as related to the fertility and current temperature sum of a site. Manuscript.

IV Nuutinen, T., Matala, J., Hirvelä, H., Härkönen, K., Peltola, H., Väisänen, H. and Kellomäki, S. 2005. Regionally optimized forest management under changing climate. Climatic Change, under revision.

CONTENTS

1 INTRODUCTION

1.1 Background

Global climate change due to greenhouse effect strengthened by human induced gas emissions (use of fossil fuels, land-use changes, etc.) has become an evident phenomenon (IPCC 2001). For the northern latitudes (e.g. Finland: 60^o-70^o N. lat.), the doubling of atmospheric CO_2 during the 21st century is predicted to be followed by an increase of up to 2 - 7°C in the annual mean temperature (T) and a 6 - 37% elevation in precipitation (Carter et al. 2002). These changes in climatic conditions are likely to enhance growth of boreal forests by a direct response to physiological processes in trees to elevated T and CO_2 but also in the long-term through longer growing seasons and enhanced mineralization of nitrogen (Linder 1987, Wang et al. 1995, Melillo et al. 1996, Hättenschwiler et al. 1997, Kellomäki et al. 1997, Myneni et al. 1997, Beerling 1999, Moore et al. 1999, Mäkipää et al. 1999, Peltola et al. 2002, Stromgren and Linder 2002; and reviews by Ceulemans and Mousseau 1994, Saxe et al. 1998, Ceulemans et al. 1999, Saxe et al. 2001).

From a forest management point of view, predicted climate change (CC) implies that current practices may need to be adapted for future conditions (Kellomäki et al. 1997, Saxe et al. 2001). By forest management it would be possible to respond to and adapt forests to the environmental changes and following changes in forest dynamics. For example, the increased stand productivity could be utilised with earlier and/or more intensive thinnings and by a shortened rotation length thereby avoiding earlier self-thinning within stands (Kellomäki and Kolström 1993, Kellomäki et al. 1997). Planning of adaptive forest management would require forestry modelling tools that are usable under CC conditions. They should be at their best both responsive to changing environmental conditions and be able to use traditional forest inventory information as inputs to produce reliable predictions on forest growth and yield for application scales of practical forestry.

The models currently used in forest management and as research tools can be classified into statistical (empirical) growth and yield models and process-based models (Mohren and Burkhart 1994, Korzukhin et al. 1996). Process-based models (physiological and gap models) generally have been developed independently of traditional statistical forest growth and yield models and vice versa (e.g. Mäkelä and Hari 1986, Ryan et al. 1996, Kellomäki and Väisänen 1997, Chertov et al. 1999a and b, Chen et al. 2000, Huntingford et al. 2000, Hynynen et al. 2002, Peng et al. 2002a, Zheng et al. 2002, Rathgeber et al. 2003). However, both these approaches aim at providing tools for analyses on forest resource management and related research (Korzukhin et al. 1996) and they also could have been developed concurrently (e.g. He et al. 1999, Baldwin et al. 2001, Lindner et al. 2002, Peng et al. 2002b).

So far, statistical models of forest growth and yield were thought to be preferable whenever locally focused and site-specific predictions have been required to support decision-making in practical forestry (Mohren and Burkhart 1994). However, their predictions are based on the assumption that the future environmental conditions are those which prevailed in the past (Korzukhin et al. 1996, Hynynen et al. 2002). Therefore, these models fail to tackle the impacts of the changing environment on the tree growth as opposed to the physiological models, in which climatic and edaphic factors interact with the growth processes of trees. Accordingly, forest growth models based on physiological processes (e.g. photosynthesis, transpiration and respiration) with hydrological and nutrient cycles as controlled by climatic factors have been generally preferred when predicting stand productivity under changing climatic conditions (Kellomäki et al. 1997, Landsberg and Waring 1997, Hasenauer et al. 1999, Constable and Friend 2000, Lindner 2000). Their usefulness has nevertheless been questioned as far as practical forest management planning is concerned (Mohren and Burkhart 1994), because of the excessive computational complexity that would arise if a detailed physiological model were to be used for large-scale forest management planning tasks. Despite this, some interest in using these models for more practical purposes has been shown, partly in connection with CC issues (Korzukin et al. 1996, Battaglia and Sands 1998, Mäkelä et al. 2000).

Recently, interest has also arisen to combine different modelling approaches to correctly predict responses of forests to environmental changes (e.g. CC), especially when the use of only one modelling approach has proven to be restrictive (Liu and Ashton 1995, Chertov et al. 1999a, Constable and Friend 2000, Porte and Bartelink 2002). As examples, one rather typical solution for CC studies has been to combine gap-type models with GIS-models or forest inventory data in order to predict changes in tree species distributions or carbon dynamics at a regional scale (Talkkari and Hypén 1996, He et al. 1999, Karjalainen et al. 1999, Sykes 2001, Ehman et al. 2002, Lasch et al. 2002, Lexer et al. 2002); or use them along with physiological process-based models (Talkkari et al. 1999, van der Meer et al. 2002). These models address the mechanisms behind the tree growth responses to CC, but usually they are not intended to make stand-level predictions for forest management units.

Should locally focused stand-specific predictions be needed for practical forest management planning, traditional growth and yield modelling could be expected to provide useful and solid base (Mohren and Burkhart 1994, Peng 2000, Porté and Bartelink 2002) to which it may be possible to incorporate some properties of physiological approaches in order to make the statistical model responsive to environmental change (Kimmins et al. 1999, Baldwin et al. 2001, Peng et al. 2002b). In this field, Peng et al. (2002b) have adopted a dynamic approach and they integrated a statistical growth and yield model with a process-based carbon balance model to create a new hybrid model for both practical forest management planning tasks and research-oriented environmental change studies. Similarly, Baldwin et al. (2001) have linked the photosynthetic production predicted by a process-based model to the site index used as the input to a statistical model, i.e. to predict the impacts of different environmental factors (including stand, climatic and edaphic factors) on forest growth and yield.

In Finnish conditions, the large-scale forestry scenario model MELA (Siitonen et al. 1996) has been widely used for forest management planning. As a part of this MELA model, the statistical growth and yield model Motti has been shown to provide reliable predictions for the full range of forests in Finland under current climatic conditions (Hynynen et al. 2002). This is because it is based on a huge body of inventory data on tree growth covering the whole of Finland. On the one hand, although these predictions are based on growth data from a large number of sample plots, they may prove biased in the future. This is because the growth equations of the model are based on growth data reflecting past climatic conditions. On the other hand, if the stand simulator of MELA system could be modified for changing environmental conditions, this would make it possible to utilise an integrated simulation and optimisation approach (e.g. Nuutinen et al. 2000, Hoen et al. 2001) in analysing forest resources also under CC conditions; i.e. to solve optimised forest management scenarios of a forest region endogenously within a model system.

1.2 Aims

The overall aim of this work was to develop a method for introducing the impacts of climate change on forest growth into a statistical growth and yield model for further applications in the context of the large-scale forestry scenario model. To achieve this purpose the study was divided into the following four tasks:

i) Comparison of the structural and functional properties of a physiological and a statistical growth and yield model in Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and silver birch (*Betula pendula* Roth.) stands under the current climate to analyse if these two approaches produce sufficiently similar results in terms of growth dynamics to provide the basis for further introduction of climate change impacts from a physiological to a statistical model (Paper I);

ii) Exploring the methodology to introduce the effects of elevated temperature (T) and CO_2 on growth of Scots pine, Norway spruce and silver birch trees into a statistical growth and yield model based on simulation data provided by a physiological model (Paper II);

iii) Extension of the transfer methodology of CC effects developed in Paper (II) for a wider application area with variation in stand location and site type (Paper III):

iv) Application of the methodology developed in Papers II-III to derive optimal forest management for a forest region located in eastern Finland (North Karelia) under changing climate in the context of the large-scale forestry scenario model (Paper IV).

2 MATERIAL AND METHODS

2.1 Outlines for the work

Three forest simulation models were utilised in this study (I-IV): i) a physiological forest growth model FinnFor (Kellomäki et al. 1993, Strandman et al. 1993, Väisänen et al. 1994, Kellomäki and Väisänen 1997; ii) a statistical growth and yield model Motti (Hynynen 2002); and iii) a forestry scenario model MELA (Siitonen et al. 1996).

The FinnFor model has been specially developed to predict the impacts of climate change on forest growth and productivity (Kellomäki and Väisänen 1997). Forest growth dynamics in the model are linked directly to climate through photosynthesis, respiration and transpiration and indirectly through the hydrological and nitrogen cycles based on physiological parameters (Kellomäki et al. 1993, Strandman et al. 1993, Väisänen et al. 1994, Kellomäki and Väisänen 1997). In contrast, growth dynamics in the Motti model are based on tree growth data from a large number of sample plots (forest inventories), and it is a statistical regression model by nature (Hynynen et al. 2002). The Motti model also forms a growth modelling part of a large-scale forestry scenario model MELA (Siitonen et al. 1996, Redsven et al. 2004), which is widely used for forest management planning in Finland. Its optimisation package, based on linear programming called JLP (Lappi 1992), can be used to select an optimal forest management solution for a region based on different optional management events simulated for individual stands in a stand simulator (Siitonen et al. 1996).

In this work, FinnFor and Motti models were compared (I) and then the Motti model was modified (II-III) to enable large-scale predictions of forest production and management in climate change conditions with the MELA system (IV) (Figure 1). As a first step, the structural and functional properties of Finnfor and Motti models were compared using Scots pine, Norway spruce and silver birch simulations under the current climate (I). This was undertaken to ensure compatibility of models prior to the incorporation of findings from the physiological model into the statistical model to make the latter responsive to climatic change. As a second step, a methodology was developed to introduce the impacts of elevated temperature and CO_2 on the growth of Scots pine, Norway spruce and silver birch trees in the statistical growth and yield model Motti based on simulation data provided by the FinnFor model (II-III). In this context, FinnFor simulations were analysed in terms of growth responses of trees to elevated temperature and CO_2 (II and III). As a final step, the methodology developed in Papers II-III was applied to derive an optimal forest management regime for a forest region located in eastern Finland (North Karelia) under a changing climate in the context of the large-scale forestry scenario model (IV).

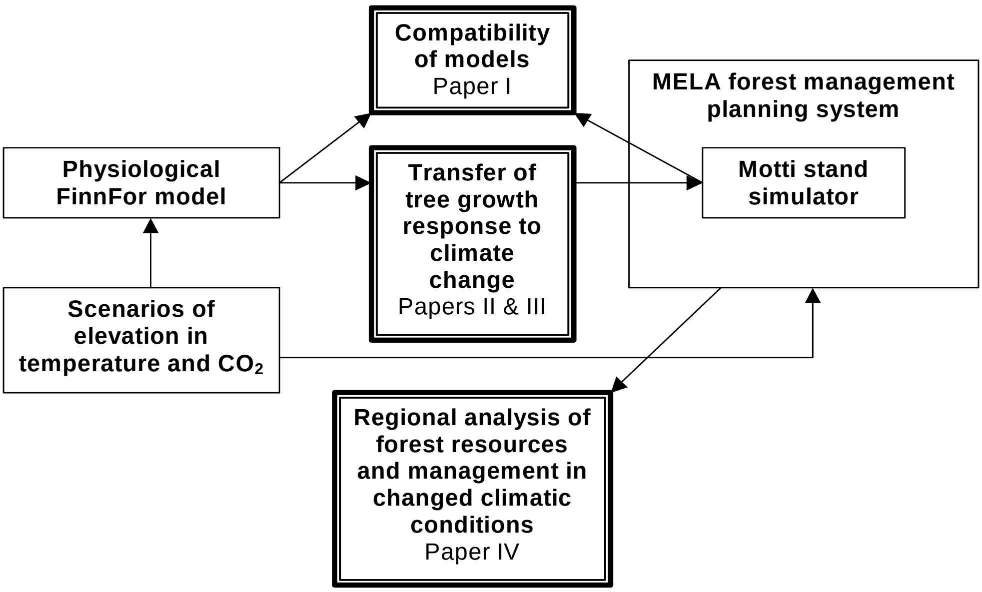

Figure 1. Outlines and models of this work.

2.2 Compatibility of two models under current climate

The FinnFor and Motti models were compared in order to analyse whether the two approaches produce sufficiently similar results in terms of growth dynamics, i.e. to provide a basis for further development of the Motti model to incorporate the effects of climate change on tree growth based on FinnFor simulations (I). The comparison was based on (i) stand-level variables, (ii) analysis of volume growth graphs (VGs), and (iii) stand structure variables. The comparison was applied to unmanaged and managed Scots pine, Norway spruce and silver birch stands growing on medium-fertility sites in the southern boreal zone in central Finland. The performance of the models was also further analysed based on simulations for a few long-term thinning experiments run by the Finnish Forest Research Institute for three stands located in southern Finland (I).

2.3 Development of transfer functions for climate change impacts from FinnFor to Motti model

Formulation of transfer functions from FinnFor simulations

Based on FinnFor simulation data, so called transfer functions were developed which enabled the use of Motti and thus MELA for climate change predictions (II, III). Functions were based on analysing the relative increment of volume growth under climate change to growth in current conditions (Relative Scenario Effect (RSEv(t)), II: Equation 1) from simulations made in FinnFor with variation in elevations of temperature (T) and CO_2 (II, III), stand structural properties and the status of a tree in a stand (II, III), site type and location of stands (III).

The formulation of transfer functions was made in a three-phase procedure: Firstly, simulations using one scenario (+4°C and 700ppm (CO_2)) with a variation in stand structures and the status of trees were analysed to formulate the basic structure of the transfer function (II: Equation 3); Secondly, simulations with a variation of elevations in T and CO_2 were analysed and modelled to formulate the transfer function for one medium fertile site with different warming scenarios (II: Equation 5); Thirdly, new simulations with additional variation in locations and site types (as implemented via nitrogen concentrations of needles, III: Chapters 2.2.1 and 2.2.2) were made and from those, impact of site type and current temperature sum (characterizing the current position in geographic space) to transfer functions were modelled (III: Equation 3, and Chapter 2.2.3). In this third phase, the number of stands and combinations of T and CO_2 elevations were diminished, but the formulation of functions relative to them remained similar to Paper II. However, as new variables were added to the function the re-estimation of parameters for whole function was required in Paper III (Table 2). Finally, the transfer function as a whole was:

$$
\begin{aligned}
RSEv(t) = {} & (\alpha_{11} + \alpha_{12}\cdot TS/1000 + \alpha_{13}\cdot(TS/1000)^2 + \alpha_{14}\cdot DOMT + \alpha_{15}\cdot DVT)\cdot T + \\
& (\alpha_{21} + \alpha_{22}\cdot TS/1000 + \alpha_{23}\cdot DOMT + \alpha_{24}\cdot DVT)\cdot CO + (\alpha_{31} + \alpha_{32}\cdot TS/1000 + \\
& \alpha_{33}\cdot(TS/1000)^2)\cdot T^2 + (\alpha_{41} + \alpha_{42}\cdot TS/1000)\cdot CO^2 + (\alpha_{51} + \alpha_{52}\cdot TS/1000)\cdot T\cdot CO + \\
& \alpha_6\cdot T^3 + \alpha_7\cdot CO^3 + \alpha_8\cdot T^2\cdot CO + \alpha_9\cdot T\cdot CO^2 + \\
& (\beta_1\cdot T + \beta_2\cdot CO + \beta_3\cdot T^2 + \beta_4\cdot CO^2 + \beta_5\cdot T\cdot CO + \beta_6\cdot T^3 + \beta_7\cdot CO^3 + \beta_8\cdot T^2\cdot CO + \\
& \beta_9\cdot T\cdot CO^2)\cdot RDFL + \\
& (\gamma_1\cdot T + \gamma_2\cdot CO + \gamma_3\cdot T^2 + \gamma_4\cdot CO^2 + \gamma_5\cdot T\cdot CO + \gamma_6\cdot T^3 + \gamma_7\cdot CO^3 + \gamma_8\cdot T^2\cdot CO + \\
& \gamma_9\cdot T\cdot CO^2)\cdot RDF,
\end{aligned} \tag{1}
$$

where T is elevation of temperature (°C) from current annual mean, CO is elevation in CO_2 from current level (350ppm), RDF is relative density factor (the sum of the minimum growing spaces of all trees in stand), RDFL is the corresponding sum for the trees taller than the subject tree, TS is temperature sum (mean of degree days between years 1961 – 1990 with threshold value +5°C) and DOMT and DVT (0/1) are the dummy variables for

Oxalis-Myrtillus and *Vaccinium* site types (if no dummies given, the model works for *Myrtillus*-type), respectively, and α_x, β_x and γ_x are the parameters. For Scots pine three site types, for Norway spruce two site types and for silver birch only one site type was modelled. The parameters were estimated using backward regression analysis (see parameter estimates of the species-specific transfer functions for Scots pine, silver birch and Norway spruce in Paper III: Table 2).

Implementing transfer functions in Motti

Basically, the transfer function was implemented in Motti, and thus the growth simulator of MELA, by adding to current volume growth the scenario-specific volume growth increment for a time step from the transfer function (II: Equation 2). In the application phase, some of the values for input variables (RDF, RDFL, ST (=site type), TS) for transfer function are derived from background information and stand data of Motti simulator and rest ones as scenario-specific input variables (T, CO) can be defined for each time step according to the climate change scenario that is used (II, III, IV). However, as Motti does not predict volume increments directly but those of diameters and heights, the additional climate scenario volume increment had to be divided between diameter and height (II: Equations 6 - 9). This was modelled based on how Motti growth models react to change in geographical variation in temperature sum in terms of height growth (II). These models were made for different tree species and for mineral soils (II) and peatlands (IV) separately. A schematic presentation of making and implementing transfer functions is described in Figure 2.

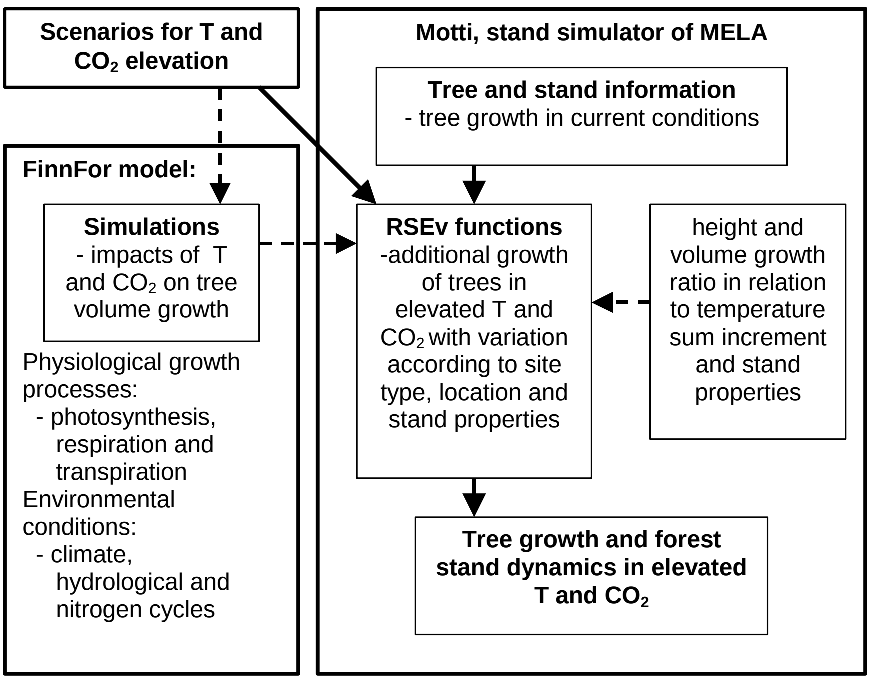

Figure 2. Procedure for implementing tree growth responses to elevated T and CO_2 from FinnFor model into MELA system. Solid arrows describe the procedure when RSEv functions are applied and dashed ones when they were produced.

2.4 Regional forestry scenario analyses: a case study of North Karelia region

Finally, the transfer functions developed above were utilised in the context of MELA forest management system for analysing future development of forest resources and management in the North Karelia region as a case study (IV). The input data for the scenario analysis were based on inventory sample plots for forest and scrubland from the ninth National Forest Inventory (NFI9, Korhonen et al. 2001). From each NFI sample plot the tree data were converted to MELA sample tree variables and the sample plot data to MELA sample plot variables (Siitonen et al. 1996). Within the MELA system, integrated simulation and optimisation (Lappi 1992, Siitonen et al. 1996, Redsven et al. 2004) calculations were used to find optimised forest management solutions for this area in different climate warming scenarios (IV).

Optimal forest management solutions for six scenarios with differences in climate and timber production were resolved for the period of 2000-2050 (IV: Table 1, Figure 4). The first set of scenarios reflected business-as-usual in terms of timber production. In the first scenario (B0), no climate change was assumed to take place. In the second (BS), annual mean temperature (T) was assumed to increase gradually by 4°C along with the concurrent doubling of the atmospheric CO_2 (from the current 350 ppm to 700 ppm) by 2100. In the third (BF), the same climate change was assumed to take place immediately and permanently at the beginning of the simulation. The constraints for business-as-usual scenarios were given as timber removal by tree species and timber assortments realised under the five-year period 1995-1999. The second set of scenarios defined maximum sustainable yield in different climate scenarios. In these second three scenarios (S0, SS, SF), the assumptions on climate were the same as in the first three. The optimisation of the sustainable timber production scenarios was constrained by the non-decreasing flow of wood, saw logs, and net income over a 50-year period and the net present value after the 50-year period greater or equal to that in the beginning. For all scenarios the objective was to maximise the net present value from timber production by using a 4 percent interest rate. In model calculations, a set of management schedules were simulated for all management units corresponding to each scenario. The results of analysis with different scenarios were then compared in terms of regional level values. (IV)

3 RESULTS

3.1 Compatibility of two modelling approaches under current climate

The predictions given by the FinnFor and Motti models under current climatic conditions agreed closely in terms of stem volume and total stem wood production in the case of the Scots pine and silver birch stands (I: Figures 2 and 3). The greatest differences were identified regarding tree size and total stem wood production for Norway spruce (I: Figures 4 and 11) and in the size distributions for Scots pine (I: Figures 8 and 9). In the silver birch stand, the predictions differed mainly in terms of tree size (I: Figure 3).

Motti gave larger values for the height and diameter of silver birch than did FinnFor, which in turn simulated taller but more slender Scots pines than Motti (I: Fig. 2 and 3).

These differences are repeated in the stocking and total growth of tree stands (I: Fig. 2 and 3). In this sense, Norway spruce clearly differed from Scots pine and silver birch, being predicted to be thicker in FinnFor than in Motti (I: Fig. 4). On the other hand, the diameter distribution showed that FinnFor simulated both larger and smaller trees than Motti (I: Fig.11). In particular, the number of trees in the smaller diameter classes was greater in FinnFor. This difference leads to larger stem volumes and total production in Motti (I: Fig. 4 and 11).

Thinning increased the diameter of all three tree species regardless of the model (I: Fig. 2, 3 and 4), and tree height (dominant height) also increased in the case of Scots pine and Norway spruce in FinnFor (I: Fig. 2 and 4) but not in Motti. This difference in the thinning response pointed to structural differences between the models. The height growth of the dominant tree in a stand is fixed according to site conditions in Motti (I: Equation 14), whereas in FinnFor it increases whenever the growth space increases. This pattern also holds well for silver birch, but to a lesser extent than for the conifers. This difference between the tree species in FinnFor is partly caused by the different size distributions of initial stands used. The initial size distributions for conifers are even whereas the shape of size distribution in a silver birch stand was evidently normally distributed. Therefore, a change in growth conditions was unlikely to have any effect on dominant height of birch stand because it would be determined by only a few large trees.

The models agreed closely in terms of relative growth rates (I: Fig. 5 – 7), especially in unmanaged stands. This implies that competition within a stand and the effect of tree position on tree growth, with the consequent growth dynamics, are quite similar in both models even though the absolute values for tree volumes or dimensions differ to some degree. These differences are propagated in the performance of the mortality model. For example, if Motti shows that the trees grow more in diameter than shown by FinnFor, this has the consequence that the number of trees decreased at a higher rate in Motti than in FinnFor. This increase in mortality resulted with a larger total stem wood production in Motti, even though stocking attains virtually the same level in both models. Stem volumes can be at the same level in these simulations, but the number of trees was can vary simultaneously.

3.2 Transfer of climate change impacts from FinnFor to Motti model

Response of tree growth to elevated T and atmospheric CO_2

The transfer functions that were developed here describe how tree volume growth is affected when mean temperature and/or CO_2 are elevated based on FinnFor simulations (II: Figure 2 and III: Figure 3). The responses in growth increment in terms of RSEv(t) as related to CO_2 and T elevation of Scots pine and silver birch are quite similar, with a clear increase in RSEv(t) values with elevations in CO_2 and T. This pattern also held well for Norway spruce, except that the increase was larger and varied more than in the case of Scots pine or silver birch in response to elevated CO_2 (II: Figure 2 and III: Figure 3). Norway spruce also differed from Scots pine and silver birch in relation to T elevation, which in contrast to other species could cause negative growth increment (RSEv) for Norway spruce if the CO_2 was not elevated simultaneously (II: Figure 2 and III: Figure 3).

Impact of stand properties and a tree's competitive status in transfer functions

Stand density and a tree's competitive status within a stand in terms of RDF and RDFL had a clear effect on RSEv's of Norway spruce and Scots pine, but no clear effect occurs with silver birch (II: Figure 1). Transfer functions (as II: Equation 3) for Scots pine and silver birch were able to explain most of the variation in FinnFor simulations, but the standard error of prediction to Norway spruce was larger (II: Table 3). The reason for this is a larger within-stand variation in Norway spruce (II: Figure 1.). As a result of the determination of the growth increment (RSEv) in relative terms, some smaller trees in Norway spruce stands with a very small absolute growth in current climate attained substantially larger values for additional growth in CC-situation in relative terms although the growth of those trees in absolute values continued to remain rather small.

There were differences in parameters of RSEv functions between tree species (II: Tables 3. and 4.). This explained that the relative reaction of growth rate to CC in Norway spruce was more similar between the FinnFor and Motti simulations than was the case in Scots pine and silver birch (II: Fig 7). Conversely, the smaller effect of the tree's competitive status (RDFL) on RSEv functions in the case of Scots pine and silver birch means that there is no difference in tree growth in relation to tree size (and competition status of the tree) between current climate conditions and CC conditions in the Motti model. Whereas in FinnFor such a difference exists, i.e. the growth of smaller trees is greater in relation to that of larger ones under CC conditions than in the current climate (II: Fig 7). Unfortunately, RSEv functions could not completely describe this phenomenon, which may also provide a partial explanation for the smaller total yield increment after CC in Scots pine and silver birch in Motti than it was in FinnFor simulations.

Impact of site type and current temperature sum in transfer function

The diversity between site types in different locations was implemented as a variation in the nitrogen concentration of needles for Scots pine and Norway spruce, when FinnFor simulations were made for final transfer functions (III). For silver birch, however, corresponding data was not available. The data used for the calculation of the nitrogen content for Scots pine and Norway spruce foliage as a function of temperature sum and site type is shown in III: Figure 2. For both species the nitrogen content increased with the increasing temperature sum. The nitrogen content also tended to be higher at sites of higher fertility and lower at sites of lower fertility, thus leading to larger simulated growth rates on more fertile sites. The effects of site type on the FinnFor simulations in relative terms (as RSEv), and thus on the transfer functions, were rather small, however, leaving most of the variation between sites to be represented by the differences inherent in the original growth model Motti to which the transfer functions were applied (III).

With regard to the temperature sum gradient, the RSEv values seemed to increase towards both the lower and higher current temperature sums in the FinnFor simulations (III: Figure 4). In the case of the northern sites (lower temperature sums) the increase in RSEv was related to a greater impact of T elevation, and for the southern sites (higher temperature sums) it was related more to a greater impact of CO_2 elevation. For silver birch, RSEv was markedly larger with lower temperature sums than with higher ones, because the nitrogen content was the same regardless of the temperature sum at the site (III: Figure 4.). With regard to variation in current temperature sum, the transfer function (III: Equation 3, Table 2) gave quite similar results to those based on simulations with the Finnfor model (III: Figure 4).

Performance of transfer functions in Motti model

The performance of transfer functions was first evaluated by a comparison of long-term simulation results between FinnFor and Motti with climate scenarios included (II: see chapters 2.3 and 3.). Thereafter, it was also evaluated by Motti model simulation results alone under CC in a range of site fertility types and geographical locations throughout Finland (implemented as current temperature sum) (III: chapters 2.3 and 3.2).

A comparison of the simulation results between FinnFor and Motti models revealed some differences regarding the behaviour of models (II). FinnFor simulations gave larger relative total yield increments in CC scenario compared to current climate than Motti simulations did for Scots pine and silver birch. Whereas for Norway spruce the opposite phenomenon was the case (II). The reason for this was the larger impact of the tree's position to growth reaction in transfer function in Norway spruce than in the other species (II). FinnFor was also more reactive to any change in environmental conditions than Motti model. For example, in thinned stands the relative increment increased more compared to increment in unmanaged stands than it did in Motti simulations (II). However, some differences in simulation results for CC scenarios were expected between models since the overall model dynamics of Motti models were not changed by transfer functions but only the growth response of trees.

Evaluation of long-term Motti simulations on different site fertility types and locations showed also that the results were logical in terms of total yield (III). All three tree species showed in principle a larger total yield in CC scenario compared to current climate. The relative yield increment was also larger the further north (smaller temperature sum) the stand was located (III: Chapter 3.2 and Figure 5). The absolute total yield was always larger in a more fertile site type in both current climate and in CC scenario simulations (III: Figure 5). However, because of the larger impact of initial Motti dynamics than that of the transfer function, the relative increment after the CC scenario was smaller in a more fertile site type compared to less fertile sites in long-term simulations (III: Chapter 3.2 and Figure 5).

3.3 Forest resources and optimised management in the North Karelia region under climate change conditions

In MELA simulations for the North Karelia region the periodic annual increment was about 4.8 $m^3ha^{-1}a^{-1}$ for both "business-as-usual" and "maximum sustainable yield" management scenarios under current climate in the first simulation period (2000-2009, IV: Table 2). For both management scenarios it increased slightly under current climate in the third simulation period (2020-2029). When compared to these results of current climate, increase in periodic annual increment could be detected already in the slow climate change scenario (IV: Table 2). Furthermore in the fast climate change scenario, the increment is 54 percent higher than under current climate already in the first period, and 70 percent higher in the third period in the "business-as-usual" scenario. In the "maximum sustainable yield" scenario the corresponding increments were 54 and 60 percent higher than under current climate, respectively.

The growing stock increased in all climate and management scenarios compared to the current value of 157 mill. m^3 (IV: Figure 5). In the "business-as-usual" scenario the growing stock reached 200 mill. m^3 under current climate in 2030, 216 mill. m^3 under the slow climate change and 321 mill. m^3 under the fast climate change. In the "maximum sustainable yield" scenario the corresponding growing stock values in 2030 were 164 mill.

m^3 , 176 mill. m^3 and 216 mill. m3, respectively. In contrast to fixed annual removal in the "business-as-usual" scenarios (4.7 mill. m^3a^{-1}), in the "maximum sustainable yield" management scenario annual removal during the simulation periods increased in all climatic scenarios from 5.25 mill. m^3 of the first period under current climate up to 10.1 mill. m^3 in the third period under the fast climate change (IV: Figure 6). This meant that accelerated growth in climate change situation (IV: Table 2) alternatively could be stored as a larger reserve in forests (in business-as-usual) or utilised more effectively as a larger removal according to the set management goal (in maximum sustainable yield).

In all scenarios the proportion of Scots pine in growing stock tended to increase as a result of the large proportion of young Scots pine forests currently in the area, but only fast climate change seemed to also increase the proportion of Norway spruce in the "maximum sustainable yield" management scenario (IV: Figure 5). Optimisation also affected management practices in different ways depending on climate change scenario (IV). For example, the proportion of removal from peatlands increased under current climate and slow climate change scenarios (IV: Figure 8). With respect to fast climate change scenario, the optimisation allocated more fellings on mineral soils (where wood extraction is cheaper) as a consequence of the increase in tree growth and cutting potential (IV: Figure 8). With regard to the management method, the proportion of cutting removal from thinnings increased in the climate change scenarios, although the removal from clear cuttings also increased in absolute terms in "maximum sustainable yield" management scenario (IV: Figure 7).

4 DISCUSSION AND CONCLUSIONS

4.1 Compatibility of the modelling approaches

The overall aim of this thesis was to develop a method for introducing the impacts of climate change on forest growth into a statistical growth and yield model Motti for further applications in MELA. The physiological model FinnFor was used as a source of information on growth reactions. With regard to this aim, the sufficient compatibility of different model types used in analysis was of primary importance. The comparison made for this purpose also served the further development of the models involved.

To determine what similar predictions Finnfor and Motti models would provide for Scots pine, Norway spruce and silver birch under the current climate, a comparison was made in the structural and functional properties of the models (I). It was found that the FinnFor and Motti models were highly comparable in the relative growth rates for all tree species, and they were also similar to each other concerning volume growth rates in Scots pine and silver birch stands. These results, along with the comparison of model predictions with observed stand data under current conditions (I: Figure 1), displayed a moderate consistency of the models.

Similar to general characterisation of different model types (Mohren and Burkhart 1994, Korzukhin et al. 1996), the Motti model as a statistical model, was found to be quite stable in its predictions and not as sensitive to initial stand conditions and management as was the FinnFor model. This implies the need to develop a responsive capacity of a statistical model if any change in stand or environmental conditions is in question. On the one hand, these results also showed that FinnFor model could be further developed for practical management situations if the proper input data was available. On the other hand, this also implied that it should be possible to incorporate some elements of growth reactions from Finnfor model into Motti model to make more precise growth predictions for wide-scale applications under the CC conditions. The latter, and also simpler approach would be beneficial since it facilitates the use of traditional forestry inventory data and currently available forest management planning system MELA in further applications.

4.2 Transfer function approach

General development of the transfer method

The method using transfer functions was developed to introduce impacts of CC on tree growth from FinnFor to Motti model (II, III). This method adhered as close as possible to the original approach of the Motti model. It meant that only the additional volume growth in CC compared with current conditions was modelled by regression analysis from the growth data generated by the FinnFor model. In this way, the species-specific transfer functions were described in terms of an increase in stem volume growth of trees as a function of elevated T and CO_2, stand density, competitive status of a tree in a stand (II), and location and site fertility type of a stand (III).

By this method, the excessive computational complexity that would arise if a detailed physiological model was used for computationally intensive, large-scale forest management planning tasks could be avoided. The compatibility with previous forestry calculations was also retained (without CC effects). If a physiological model had been used instead in MELA system (IV), the simulation results even in the absence of CC, would differ to some degree from those obtained with the original growth model (Motti) (I). Moreover, it was assumed that the CC effects on growth are direct and gradual. Such changes could be introduced into the Motti model without impairing its inner logic. Accordingly, the changes that would have radical effects on the stand dynamics or that would be delayed through increased mineralization of nitrogen, were outside the scope of this study.

Very few efforts that would be comparable to this transfer approach have been made (Baldwin et al. 2001, Peng et al. 2002b). In both of those systems, the process-based and statistical models have been used concurrently for CC predictions; i.e. to form a new hybrid model (Peng et al. 2002b), or to develop a two-way link between models (Baldwin et al. 2001). By contrast, the method presented in this study makes it possible to make predictions on forest growth under CC with the statistical growth and yield model alone with no need to utilise physiological modelling in the application phase.

Performance of the transfer functions

A comparison of the simulation results obtained with FinnFor and the modified Motti model revealed some differences in behaviour between the models under the CC conditions (II). They were mainly caused by differences in the internal dynamics of the original models, but also parameters of transfer functions had species-specific effects (II). The total yield used in these comparisons reflected the production capacity of the stand during the rotation time; the increase in total yield under the CC relative to the current climate gave a rough estimate of the effect of the transfer variables at the stand level (II). Moreover, the succession of other variables was also useful for determining the reasons for the variations between the model predictions. As was found in Paper I, it could also be recognised here

(II) that FinnFor was more sensitive to stand management than Motti. The response to CC was greater in thinned stands than in unmanaged ones in FinnFor, whereas CC affected both management options similarly in Motti (II). This shows that the reaction capacity to the changing conditions of the physiological models cannot be transferred totally into the statistical model by this method.

Simulations with the Finnfor model showed that increasing site fertility enhanced the growth response to elevated T and CO_2, although the effect of site type on the RSEv values was fairly small, albeit statistically significant (III). This impact of site fertility type was added, therefore, to the transfer functions (for Scots pine and Norway spruce) in the form of a dummy variable, with a consequent difference in increased productivity between the site types (III).

The effect of current temperature sum (characterizing the geographic location) on RSEv was somewhat larger than that of the site fertility type, especially with the co-effect of T, while the impact of CO_2 reversed this dependence on T and current temperature sum in the models for Norway spruce (III). A more pronounced effect of T at low current temperature sum was to be expected (III), because low summer temperature limits growth more in northern than in southern Finland (Mäkinen et al. 2002). Similarly, in provenance experiments trees of northern origin have been found to benefit more from increasing temperatures (Beuker 1994). Also in this work (III), the simulations' results were in line with the assumptions regarding Scots pine and silver birch, which reacted to elevated T more vigorously at sites with a low current temperature sum. In Norway spruce, however, the impact of CO_2 on the values of RSEv was greater than that of T, with the consequence that the impact of elevated T was lower over the thermal gradient covering Finland.

Limitations of the approach

The decision to keep the basic dynamics of the Motti model untouched but only change the growth predictions, guaranteed more stable behaviour of transfer functions within forest stand dynamics when applied in forest management planning tasks in MELA. Of course this simplification left some questions open concerning CC impacts.

As the same mortality models, which include individual tree survival probability and self-thinning (Hynynen 1993, Hynynen et al 2002), were applied in both the FinnFor and Motti models (I), any problems related to possible changes in tree mortality as a consequence of CC were outside the scope of this work (II). However, the self-thinning line was increased slightly for Scots pine and Norway spruce after height growth increment by transfer functions and the subsequent increase of site index, which is one factor in the self-thinning models of Motti (Hynynen et al. 2002, Hynynen 1993, II). Generally, this traditional formula for self-thinning (number of living trees in a stand related to the square of their mean diameter) has proved to be a rather robust basis for the prediction of natural mortality of trees in a stand (Hynynen 1993, Río et al. 2001). Further research would be needed on how realistic is the definition of the current self-thinning line by which most of the increased growth due to CC contributes to natural mortality once the self-thinning line has been reached. Problems of this kind are, however, of minor interest when only managed forests are concerned, because management practices usually aim at stands not to attain the self-thinning line.

Impacts of CC on regeneration or early juvenile growth were not studied here. In addition, the transfer functions were not used to describe the effect of CC on tree growth before they have passed 1.3 m in height (II). This decision was based on Finnfor simulations (unpublished data), in which no reason was found to accelerate height growth of saplings by means of any transfer variables in the Motti model.

Moreover, it should be kept in mind that the application area of transfer functions developed in this work (II, III) should be confined within the range found in the simulated data (i.e. inputs for tree/stand variables, CO_2, T, site fertility type, and location). New transfer functions would be needed if the method is intended to be used for a wider application area or if environmental factors other than described here were to change substantially and have effects on tree growth.

4.3 Climate change impacts in regional simulations

For regional applications, the transfer function methodology developed in this work (II-III) was implemented in the MELA system to derive optimised forest management for the forest area of North Karelia under changing climate (IV). In this context, the integrated simulation and optimisation of forestry scenario model MELA (Siitonen 1996, Redsven et al. 2004) and NFI sample plot and tree data for the forest region of North Karelia (Korhonen et al. 2001) was utilised.

The periodic mean annual increment in the first simulation period under current climate was found to correspond closely with the latest NFI results (Korhonen et al. 2001) indicating the reliability of the growth models in MELA (IV). If climate was assumed to stay as current, the periodic annual increment increased during the later simulation periods due to the change in the composition of forests, and especially due to the increase in average growing stock. The comparison of the periodic annual increment between the current climate and different climate change scenarios demonstrates the performance of transfer functions. The effect of climate change was already detected in the slow climate change scenarios but appeared more clearly in the fast climate change scenarios. The effects of climate change here (IV) were at the same level as the relative growth increments of single stands for similar scenarios when the climate change transfer functions were developed and tested (II). However, it should be kept in mind that the regional composition of forests could change depending on the management scenario, which may concurrently affect the periodic annual increment. As an example, the increase of periodic annual increment during the simulation in the fast climate change was partly due to the increase in average growing stock.

Differences in growing stock and cutting removal between current climate and gradually changing climate were not large neither in business-as-usual nor in sustainable timber production scenarios (IV); the changes in growing stock were clearly seen as late as in the third simulation period. The calculation period applied may, therefore, be too short to show clearly the impacts of a gradually changing climate. As a comparison, in the fast climate change scenario, the impacts of climate change were reflected also in forest management practices. For example, the proportion of removal from thinning had already increased in the second simulation period. This may indicate that stands fulfilled the thinning requirements earlier in CC than under current climate. However, the increase in cutting removal from thinning and from peatland during the 30-year period was partly due to the initial regional composition of forests. Although these fast climate change scenarios should be taken as theoretical, they were useful in demonstrating the direction of change. The comparison of the different climate scenarios showed that the effects were in the same direction irrespective of the level of change.

As a result of Scots pine domination, the proportion of Scots pine in growing stock appeared to increase in all scenarios (IV). In the business-as-usual scenarios the Norway spruce dominated cuttings strengthened the effect. However, the acceleration of growth rate due to climate change differs by tree species. For example, in the fast climate change the proportion of Scots pine in growing stock increased less than in other climate scenarios. Correspondingly, the proportion of Norway spruce increased considerably compared to other tree species. This was expected because in transfer functions Norway spruce showed the largest relative growth increments (II and III).

On the one hand, in the sustainable timber production scenarios the cutting potential from current and future forests over a region were utilised effectively. On the other hand, the business-as-usual scenarios represented the simulation approach usually applied in climate change impact studies. These current market-driven (business-as-usual) scenarios appear also to correspond to the regional forest programme in North Karelia (Pohjois-Karjalan…2002), which expresses the regional forestry interests of society. In a way, this scenario seems to be a safe choice because the total removal is clearly below the maximum sustainable yield and, consequently, the growing stock increases more compared to management by maximum sustainable yield scenario (IV).

Although empirical data to confirm these future predictions is naturally not available, other modelling predictions (Talkkari 1996, Nabuurs et al. 2002) show an increase in growth and felling possibilities in a similar direction as this study (IV). However, there are still uncertainties about the regional characteristics of the future climate as well as about the response of the Finnish forests to the changes in climatic conditions. In addition, the changes in market prices or the restrictions in timber production may further affect the optimal forest management at regional and national level.

4.4 Concluding remarks

A comparison of physiological and statistical models revealed a potential to develop these fundamentally different model types concurrently. This could be utilised in developing a transfer function method to introduce the effect of elevated T and CO_2 on tree growth to a statistical model based on physiological model simulations. When these transfer functions were implemented in a forest management planning system, sustainable timber production with optimised forest management at regional level under climate scenarios could be solved endogenously. This will offer new means to adapt and mitigate the impacts of climate change to Finnish forests by studying the optimal forest management corresponding to different socio-economic requirements and its sensitivity under different climate change scenarios.

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