

**Dissertationes Forestales 42**

Effects of management on timber production and carbon  
stocks in a boreal forest ecosystem under changing  
climate: a model based approach

Jordi Garcia-Gonzalo

Faculty of Forest Sciences  
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Academic dissertation

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## ABSTRACT

In this thesis a process-based growth and yield model was used to investigate: (i) the sensitivity of timber production (paper I) and carbon (C) stocks (paper II) to management (i.e. five thinning regimes and one unthinned regime) under different climate scenarios (i.e. current climate, ECHAM4 and HadCM2) at the level of the forest management unit (FMU); and (ii) the effects of initial age class distributions (i.e. normal, equal, left- and right- skewed distributions) of an FMU on timber production and C stocks under different management and climate scenarios, with implications on the cost of C sequestration over the next 100 years (paper III). Moreover, the integrated use of a process-based growth and yield model, a wood products model and a multi-objective optimisation heuristic allowed the investigation of how climate change may affect optimal planning solutions for multi-objective forest management in an FMU (paper IV). The different management objectives considered timber production, C sequestration (in situ as well as in wood products) and biodiversity (in terms of deadwood). Simulations over the next 100 years were undertaken with ground true stand inventory data of a forest management unit (1451 hectares) made up of a mosaic of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and silver birch (*Betula pendula*) stands in central Finland.

The gradual increase in temperature and precipitation with a concurrent elevation in CO<sub>2</sub> over the simulation period enhanced timber production and C stocks. Regardless of the climate scenario and initial age class distribution used, any thinning regime allowing a higher tree stocking than business-as-usual management over the rotation increased the timber production and simultaneously maintained or increased the C stock in the forest ecosystem compared to business-as-usual management (papers I-III). On the other hand, the maximum C stock in the forest ecosystem was reached in the unthinned regime, but it also gave the lowest net present value. The initial age class distribution had more effect on timber production (up to 20% difference) than on average C stock in the forest ecosystem (3%) (Paper III). When optimising the management plans within the FMU, under changing climatic conditions, the share of allocated management regimes differed between the management objective scenarios as well as between the climate scenarios within each objective scenario (Paper IV). The relative increase in the utility of optimised plans due to climate change differed somewhat between the objective scenarios. As a conclusion, the integrated use of process-based model and wood products model together with multi-objective optimisation appears to be a promising approach for multiple-use management planning under conditions of climate change.

**Keywords:** Process-based growth and yield model, climate change, boreal forest, management, timber production, carbon stocks, multi-objective optimisation, wood products model, forest planning, heuristic optimisation.

## ACKNOWLEDGEMENTS

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Joensuu, May 2007

Jordi Garcia Gonzalo

## LIST OF ORIGINAL ARTICLES

This thesis is a summary of the following papers, which are referred into the text by the Roman numerals I-IV:

- I. Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E., Kellomäki, S. 2007. Effects of climate change and management on timber yield in boreal forests, with economic implications. Submitted manuscript.
- II. Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E., Kellomäki, S., 2007. Changed thinning regimes may increase carbon stock under climate change: A case study from a Finnish boreal forest. *Climatic Change* (81) 431-454. doi:10.1007/s10584-006-9149-8
- III. Garcia-Gonzalo, J., Peltola, H., Zubizarreta Gerendiain, A., and Kellomäki, S. 2007. Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate. *Forest Ecology and Management* (241): 243-257. doi:10.1016/j.foreco.2007.01.008
- IV. Garcia-Gonzalo, J., Jäger, D., Lexer, M.J., Peltola, H., Briceño-Elizondo, E., and Kellomäki, S. 2007. Does climate change affect optimal planning solutions for multi-objective forest management?. *Allgemeine Forst und Jagdzeitung* (AFJZ). In press.

Jordi Garcia-Gonzalo had main responsibility in regard to the entire work done in Papers I-IV. But Mr Dietmar Jäger and Prof. Manfred Lexer helped with the optimisation of the utility model in Paper IV and the co-authors of separate Papers (I-IV) have commented the manuscripts.

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# 1 INTRODUCTION

## 1.1 Timber production and carbon stocks under changing management and climatic conditions

The future climate is expected to change substantially due to the rapid increase of greenhouse gases in the atmosphere, especially carbon dioxide (CO<sub>2</sub>) (IPCC 2001, Carter et al. 2002). For example, in Finland the future climate is probably characterised by an increase of 2-7°C in annual mean temperature (T) and an increase of 6-37% in precipitation with a concurrent doubling of CO<sub>2</sub> by 2100 (Carter et al. 2002, Kellomäki et al. 2005). The growth of boreal forests in northern Europe is currently limited by the short growing season, low summer temperatures and short supply of nitrogen (Kellomäki et al. 1997a,b, Nohrstedt 2001, Olsson 2006). Thus, the expected increase in T may prolong the growing season and enhance the decomposition of soil organic matter, thereby increasing the supply of nitrogen (Melillo et al. 1993, Lloyd and Taylor 1994). This may substantially enhance the forest growth, timber yield and accumulation of carbon (C) in the boreal forests (Giardina and Ryan 2000, Jarvis and Linder 2000, Luo et al. 2001, Strömgren 2001).

The boreal forest landscape consists of a mosaic of separate stands that have varying growth rates and productivity due to differences observed in site fertility, tree species composition, and age. Thus, the structure of the forest landscape is one of the key factors affecting the timber yield and C stocks over larger areas. Newly regenerated sites probably lose C, whereas young stands gain C. In maturing stands, the C gain reduces along with the declining growth, and over-mature stands may even lose C (Jarvis et al. 2005). Therefore, the sustainable management of forest landscape requires that the stands represent different stages in the life cycle of trees in order to ensure an appropriate balance between timber production and C stocks in the forest ecosystem. Because the climatic conditions influence the growth and development of forest stands, it could be expected that climate change will affect the dynamics of forest landscapes and, thus, the timber production and C stocks as well.

Until fairly recently, little has been known about how climate change may affect the management response of the forest ecosystem as regards the timber production and C sequestration. Thus, there is a clear need to better understand their interaction in order to efficiently utilise the increasing potentials for timber production and C sequestration and in order to develop appropriate management strategies under climate change (Lindner 1999). Management has also several direct and indirect influences on the productivity of forest ecosystems and their C sequestration potentials (Karjalainen 1996a, b, Nabuurs and Schelhaas 2002). Previous model-based studies have indicated that the total ecosystem C pools in unmanaged boreal forests are significantly larger than those in managed forests when applying the business-as-usual management rules (Bengtsson and Wikström 1993, Karjalainen 1996b, Thornley and Cannell 2000, Finér et al. 2003). On the other hand, an increase in growth and yield and consequently increase in C stocks can be observed in the boreal forests regardless of management under climate change (e.g. Pussinen et al. 2002). However, there may be a need to adapt the current management to the altered dynamics of the forest ecosystem in order to avoid possible harmful effects on the forests and to optimally utilise the increasing growth and yield under climate change (Lindner 2000, Lasch et al. 2005, Briceño-Elizondo et al. 2006, Fürstenau et al. 2006).

One of the main issues to be considered in the future is the fact that the preference of C in the management may induce opportunity costs for timber production. Thus, it is important to investigate how the timber production and C sequestration should be combined in order to balance these two management objectives in a sustainable way and how the structure of a managed forest landscape should be shaped to ensure simultaneous production of timber and C sequestration. Nevertheless, the forest management can still be a cost-effective means of enhancing C sequestration of forests, particularly when C storage in wood products is considered (Kauppi et al. 2001, Pussinen et al. 2002). In addition, sustainable forest management (e.g. MCPFE 1998) has to simultaneously consider other forest functions and services beyond timber production, such as C sequestration, maintenance of biodiversity, production of drinking water (e.g. Vacik and Lexer 2001, Köck et al. 2002) as well as various protective functions in mountain forest (e.g. Köchli and Brang 2005). However, the multiple-purpose approach needed for sustainable forest management may require trade-offs among conflicting objectives. For example, measures to enhance the C sequestration in managed forests may need changes in the current silvicultural practices, e.g. thinnings, rotation length and fertilisation, which in turn may affect timber production (Cannell and Dewar 1995, Karjalainen 1996a, Schlamadinger and Marland 1996, Seely et al. 2002).

## **1.2 Tools available for impact analyses**

Empirical growth and yield models are widely used to support decision-making in forestry. Usually, these models utilise inventory data representing the past growth and development of a forest. The applications of such models in simulating the future growth and development assume that the future growing conditions are similar than in the past. Therefore, any changes in the growing conditions may bias the simulated growth and development. Optionally, one may use Gap or Patch models (Botkin 1993), which explicitly assess the impacts of temperature, water and nutrients on growth and development of trees. However, the main goal of these models is to simulate vegetation patterns over time based on (i) the regeneration, growth and death of individual trees, and (ii) the interaction between different tree species. The Gap models are used, for example, for assessing the potential vegetation patterns and changes in the vegetation distribution under climate change. Nevertheless, the Gap models normally exclude physiological mechanisms linking the growth and development of trees with the climatic and edaphic factors. This may limit their applicability for impact studies compared to mechanistic models or process-based models, which include physiological response mechanisms to changes in environmental conditions (Waring and Running 1998).

Until now, the use of process-based models in forestry decision-making has been limited. This is because the application of these models may require, for example, data not provided by conventional forest inventories. However, process-based models can provide the same prediction capacity under practical management situations as empirical models (Matala et al. 2003). Moreover, process-based models may help to understand, how forests grow and develop under climate change (Landsberg and Waring 1997, Sands et al. 2000) and how management could be modified in order to avoid detrimental impacts and utilise the opportunities probably provided by climate change (Lindner 2000).

In recent years several process-based models have been developed and applied successfully to study forest growth and dynamics under climate change (e.g. Kellomäki et



al. 1997a,b; Thornley and Cannell 2000, Mäkelä et al. 2000a, b, Sabaté et al. 2002). Most of these studies have focused on the assessment of how forests grow under climate change by applying the current management practices, and mainly at the stand level. Until now, the use of process-based models at the level of forest landscape or forest management unit (FMU) has been limited. Moreover, only a few studies deal with multi-objective forest management under climate change, but none of them includes the optimisation of management forest plans. For example, Lasch et al. (2005) and Fürstenau et al. (2006) have analysed alternative management plans for an FMU in Brandenburg, Germany, where the operational stand treatment plans had been derived from alternative strategic management concepts at the FMU level. Based on these studies, the simulated impacts of different climate change scenarios on forest ecosystem services and functions were found to be substantial depending on initial site and stand conditions and the management strategies.

The expected climate change impacts on the forest dynamics raise the question of how to adapt and sustain the forest production in the future over a large area. If multiple objectives have to be considered, the combination of multi-criteria decision making (MCDM) techniques with the optimisation heuristics are frequently applied (e.g. Pukkala 2002). MCDM is employed to compare the objective variables in a joint utility function, which can be maximised by means of an optimisation heuristic. Surprisingly, the issue of optimising the forest management under climate change has not attracted much attention so far. One of the few examples has been presented recently by Nuutinen et al. (2006), who employed linear programming to optimise timber production at a regional scale for a planning period of 30 years under climate change. Different approaches applicable to optimise the multi-goal forest production have been recently presented, for example by Kangas and Hytönen (2001), Kangas et al. (2001), Bettinger et al. (2002), Falcão and Borges (2002) and Kurttila and Pukkala (2003).

### 1.3 Aims of the study

The sensitivity of timber production and C stocks to management in a boreal forest ecosystem under changing climatic conditions was assessed using a model based approach. More specifically, this study has the following research tasks:

- I. To investigate the sensitivity of timber production to management under changing climatic conditions in a boreal forest ecosystem (**Paper I**).
- II. To investigate the sensitivity of carbon stocks (C in soil, C in above- and below-ground tree biomass) and C in harvested timber to management under changing climatic conditions in a boreal forest ecosystem (**Paper II**).
- III. To investigate the effects of different initial age class distributions of a boreal forest ecosystem on the timber production and C stocks (incl. C in soil, C in above- and below-ground tree biomass) under different management and climate scenarios. In this context, an approach to calculate the cost of C sequestration was used (**Paper III**).
- IV. To investigate how climate change affects optimal planning solutions for multi-objective forest management at the ecosystem level. The study is based on the

integrated use of a process-based growth and yield model, a wood products model and a multi-objective optimisation heuristic considering as objectives timber production, C sequestration, and biodiversity (in terms of deadwood) (**Paper IV**).

## 2 MATERIAL AND METHODS

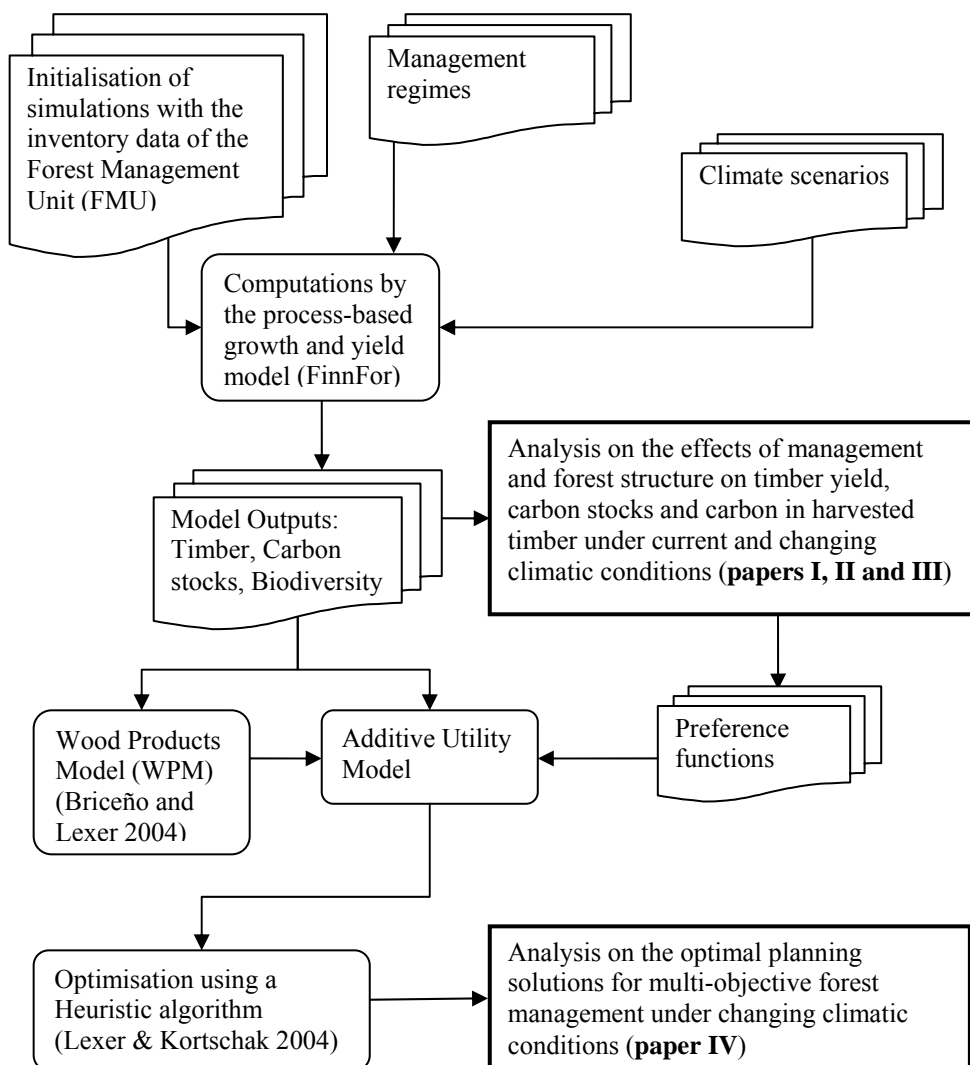
### 2.1 General outlines for the work

The outline of the work is presented in **Figure 1**. The study utilised a process-based growth and yield model (FinnFor) originally designed by Kellomäki and Väisänen (1997) to simulate the development of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and silver birch (*Betula pendula*) stands growing in boreal conditions. The model provides predictions on the photosynthetic production, growth, timber yield, carbon and water balance of the stands in response to different environmental conditions (climate, soil) and management regimes (Strandman et al. 1993; Kellomäki et al. 1997a,b, Kramer et al. 2002, Matala et al. 2003).

The model was applied for assessing the effects of forest management and climate change on the timber production and carbon (C) stocks in a boreal forest ecosystem for an FMU located in central Finland, with implications on the C stock in harvested timber (Papers I-IV). More specifically, (i) an appropriate management strategy was outlined with regard to timber production (Papers I, III-IV), C stock in the ecosystem (Papers II-IV), and C in harvested timber (Papers II and IV), and (ii) the effect of climate change on optimal planning solutions for multi-objective forest management was analysed (Paper IV). Simulations covered 100 years using three different climate scenarios (current climate, ECHAM4 and HadCM2), five thinning regimes and one unthinned regime. Simulations were based on ground-true stand inventory data (1451 hectares) representing Scots pine, Norway spruce and silver birch stands. The simulation outputs analysed under the varying management and climate scenarios included the following variables: (i) timber production in terms of harvested timber and net present value (NPV), (ii) C stocks in forest ecosystem in terms of C in soil, C in above- and below-ground tree biomass, and (iii) C stock in harvested timber. The sensitivity of these output parameters to the structure of forest landscape (initial age class distribution) under different management and climate change scenarios was also analysed (Paper III). In this context, the cost of C sequestration was calculated.

Finally, a heuristic optimisation of forest management under different climate scenarios was applied (Paper IV). In this context, a wood products model (WPM) (Briceño-Elizondo and Lexer 2004) was used to calculate C resilience times within different wood product categories. The output data from the WPM was used, along with the results of forest stand simulations, in a multi-attribute utility model to calculate a utility index for the optional management strategies at the management unit level. In order to optimise forest management, the utility function was maximised by a heuristic taking into account three different objective scenarios representing contrasting views on forest management objectives. Two scenarios had a clear focus on a single objective, timber production (MaxTP) and C sequestration (MaxCS), respectively. The third scenario (multi-objective;

MO) assumed an equal importance of different management objectives (timber production, C sequestration and biodiversity). In this context, the effect of climate on the optimised management plans was analysed, and the potential benefits of considering climate change in the forest planning was evaluated.

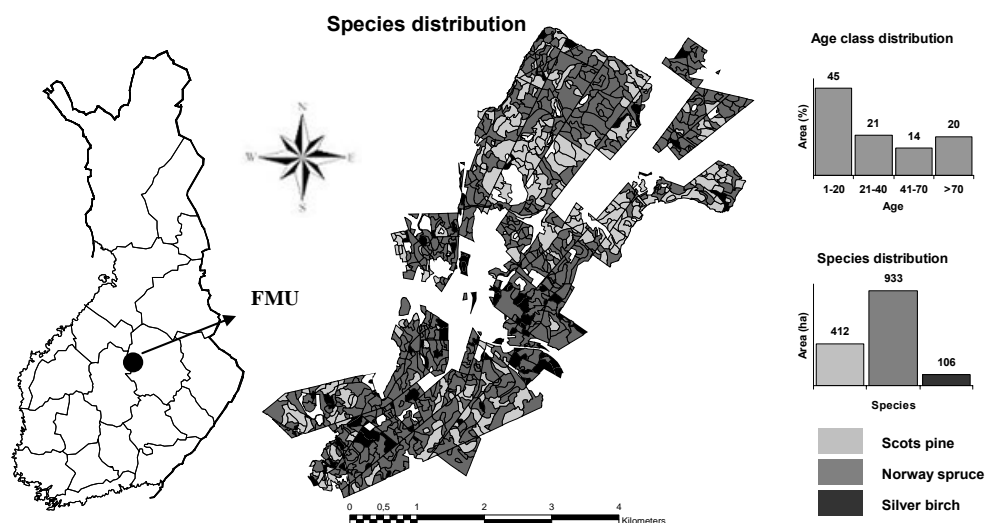


**Figure 1.** Outlines of the study with links between different model components used in the study.

## 2.2 Study area, management and climate scenarios applied

### 2.2.1 Study area (Papers I-IV)

The FMU used in this study was located in central Finland, near Kuopio (63°01'N 27°48'E, average altitude 94 m above sea level). It consisted of about 1451 hectares (1018 stands) of forests inventoried in 2001 (**Figure 2**). The stands dominated by Norway spruce (*Picea abies*) accounted for 64% of the total area (933 ha), while Scots pine (*Pinus sylvestris*) dominated stands covered 28% (412 ha), the rest of the area (106 ha) was covered by silver birch (*Betula pendula*). The sites were of *Oxalis Myrtillus* (OMT), *Myrtillus* (MT) and *Vaccinium* (VT) types (Cajander 1949). Most of the stands were located on MT sites representing medium fertility (621 stands, 876 ha). A total of 170 stands were located on the poor VT sites (275 ha) and 227 stands on the most fertile OMT sites (300 ha). The most abundant tree species on the fertile sites (OMT, MT) was Norway spruce, whilst on the poor sites (VT) Scots pine was the most abundant species. For each stand, available information included dominant tree species, average stand age, height and diameter at breast height (both weighted by basal area), stand density (trees ha<sup>-1</sup>) and soil fertility type. The original age class distribution of the tree species in the FMU is presented in **Figure 2**.



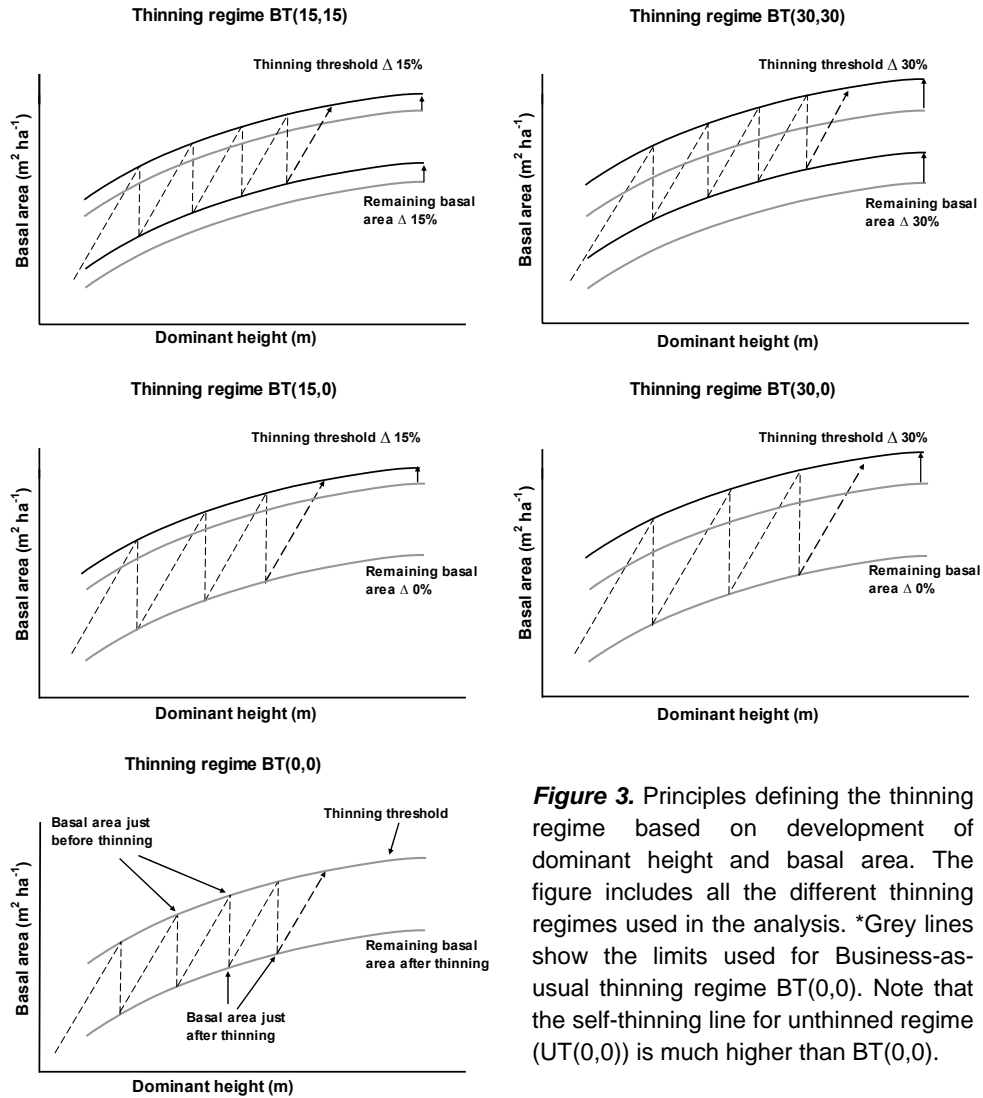
**Figure 2.** Location of the Finnish study area including a map of the forest management unit (FMU) showing the current species distribution in the FMU, and including graphs for the initial age class distribution and dominant species (area).

### 2.2.2 Management alternatives (Papers I-IV)

The management recommendations applied until recently in practical Finnish forestry (Yrjölä 2002) were used to define the business-as-usual stand treatment programme (STP); Basic Thinning BT(0,0). The recommendations are species- and site-specific, and they employ the dominant height and basal area for defining the timing and intensity of thinning (**Figure 3**). In this work, the thinning recommendations were applied so that whenever a given upper limit for the basal area (thinning threshold) at a given dominant height is encountered, a thinning intervention is triggered. In this work, stands were also thinned from below and trees were removed to achieve the basal area recommended for a respective dominant height. Thus, the timing of thinning was adjusted to the growth and development of the tree population to take place before the occurrence of mortality due to crowding. This is valid in the stands with a dominant height  $\geq 12$  m, which is the threshold for dominant height to allow thinning. Prior to this phase, trees are susceptible to natural mortality as a result of overcrowding. In order to simplify the calculations, the thinning rules for the MT and OMT site types (which together accounted for 83% of the area) were used for all stands in the simulations.

The basic thinning regime given in the management recommendations (Yrjölä 2002) can be varied in many ways by combining changes in the thinning threshold as well as in the remaining basal area after thinning. Therefore, to limit the final number of the thinning regimes applied, a preliminary analysis was carried out in which the basal area remaining after thinning and the thinning threshold were varied (0%,  $\pm 15\%$  and  $\pm 30\%$ ) constructing a matrix of 25 thinning regimes. Then the development of Scots pine, Norway spruce and silver birch stands (with 2500 saplings  $\text{ha}^{-1}$ ) was simulated growing on MT site type over the 100 years with a fixed final clear cut at the end of the simulation period. In addition, each of the species was simulated without thinnings, by applying only a clear cut at the end of the simulation period. According to these analyses, only a limited number of regimes provided at least an equal amount of timber compared to current recommendations (business-as-usual). Furthermore, regimes with a large number of thinnings with a small volume of harvested timber were excluded. In such cases, the economic profitability was expected to be very low for any forest owner or forest company (based on stumpage prices). The only thinnings that fulfilled these criteria were those where the upper limit that triggered thinning was increased, either alone or concurrently with the remaining basal area (compared to current recommendations). In all, six management regimes (referred to as stand treatment programmes - STPs - in Paper IV) were used for further analyses for each of the three tree species. The management regimes consisted of five thinning regimes (**Figure 3**) and one unthinned regime.

The five thinning regimes selected for detailed analyses were: Basic Thinning BT(0,0); two regimes based on variation in the thinning threshold which was increased by either 15% or 30% (BT(15,0) and BT(30,0)); and two regimes which combined changes in both limits, an increase of the thinning threshold by 15 or 30% and a corresponding increase in the remaining basal area in the stand after thinning, ((BT(15,15) and BT(30,30)). These changes allow higher stocking to be maintained in the forests over the rotation compared to BT(0,0). Additionally, a regime without thinnings over the rotation was simulated for all species, by applying only a final clear cut (UT(0,0)).



**Figure 3.** Principles defining the thinning regime based on development of dominant height and basal area. The figure includes all the different thinning regimes used in the analysis. \*Grey lines show the limits used for Business-as-usual thinning regime BT(0,0). Note that the self-thinning line for unthinned regime (UT(0,0)) is much higher than BT(0,0).

The simulations for the FMU covered a 100-year period. Regardless of tree species and site types, in all management regimes the stands were clear cut at an age of 100 years at the latest, or earlier if the average diameter at breast height (DBH) of the trees exceeded 30 cm. These criteria for final cutting were adopted from the Finnish management guidelines (Yrjölä 2002). After clear-cutting, the site was planted with the same species that occupied the site prior to harvest. The initial density of the stands was  $2500 \text{ saplings ha}^{-1}$  regardless of the site and tree species. Once the stand was established, the simulation continued until the end of the 100-year period.

### 2.2.3 Climate scenarios (Papers I-IV)

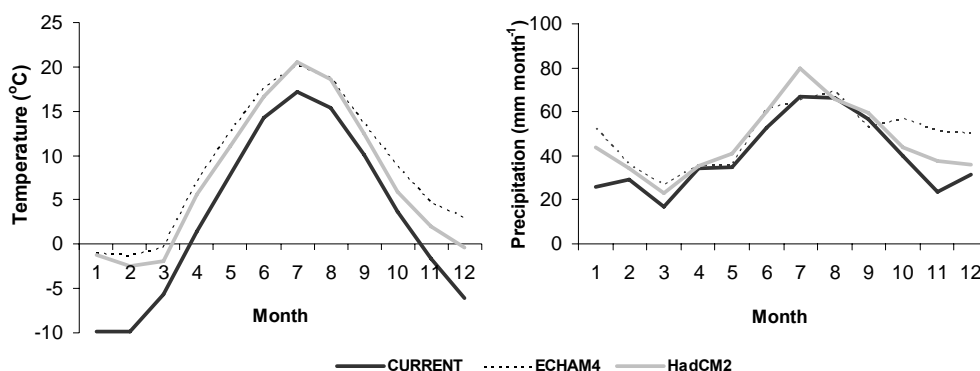
Three different climate scenarios over 100 years were used in the simulations; i.e. current climate and two transient climate change scenarios. The current climate was represented by the detrended weather data of the reference period 1961-1990, which was repeated consecutively to cover the entire 100-year simulation period. The first climate change scenario was based on the output from the global circulation model (GCM) HadCM2 (Erhard et al. 2001, Sabaté et al. 2002). The second climate change scenario was based on the ECHAM4 climate data compiled by the Max Plank Institute, Hamburg, Germany. The data for both climate scenarios were based on the greenhouse emission scenario IS92a (Houghton et al. 1990). The climate data for the study were provided by the Potsdam Institute for Climate Impact Research (Kellomäki et al. 2005).

In the scenario representing the current climate, the annual mean temperature and precipitation for the period 2071-2100 were 3.1 °C and 478 mm yr<sup>-1</sup>, respectively. Under the HadCM2 climate, for the same period, these figures were 7.2 °C and 563 mm yr<sup>-1</sup>. Under the ECHAM4 climate, the values of annual mean temperature and precipitation were greater than under the HadCM2 climate; i.e. 8.6 °C and 591 mm yr<sup>-1</sup>. The seasonal variation of temperature and precipitation for the three climate scenarios are shown in **Figure 4**.

Under the current climate, the CO<sub>2</sub> concentration was kept constant at a value of 350 ppm, whereas in addition to the increase in temperature and rainfall, the HadCM2 and ECHAM4 climate scenarios presupposed a gradual and nonlinear increase up to 653 ppm over the period 2000-2100. The increment in CO<sub>2</sub> concentration ([CO<sub>2</sub>]) during the early phase of simulation was smaller than that in the latter phase and followed Eq. (1),

$$CO_2(t) = 350 \times \exp(0.0063 \times t) \quad (1)$$

where  $t$  is the year of simulation and 350 ppm is the initial CO<sub>2</sub> concentration in the first year of simulation ( $t = 0$ , the year 2000). Relative humidity and radiation were not affected by the scenarios.



**Figure 4.** Mean monthly temperature (°C) and precipitation (mm) in the last 30 years of the simulation period (2071-2100) for the three climate scenarios used in the study.

## 2.3 Modelling approaches

### 2.3.1 Process-based growth and yield model (Papers I-IV)

*Outlines for the model.* In the process-based growth and yield model, FinnFor, the dynamics of the forest ecosystem are directly linked to the climate (e.g. temperature, atmospheric CO<sub>2</sub>, precipitation, radiation) through photosynthesis, respiration and transpiration calculated on a daily basis (Kellomäki and Väisänen 1997). Furthermore, hydrological (water availability) and nutrient (e.g. nitrogen availability) cycles indirectly couple the dynamics of the ecosystem to climate change through soil processes (**Table 1**). The physiological and ecological performance of trees are calculated on a cohort basis. Each cohort is defined by the tree species, the number of trees per hectare, DBH (cm), height (m) and age (year). These variables are used as the inputs of the initial stand data for the simulations and they are updated annually during the simulation. The computations cover an entire year representing active and dormant seasons. The photosynthetic production is used to calculate the tree growth.

In the model, stocking controls the dynamics of the ecosystem through mortality and management by modifying the structure of the tree population, with resulting changes in canopy processes and availability of resources for physiological processes and consequent growth. In this context, the growth response of individual trees to the thinning is related to the gradual increase of needle mass of the trees. The rate of tree mortality is updated every five-years by calculating the probability of survival of trees in each cohort with regard to: (i) the stocking in the stand, (ii) classification of the tree status in a stand (dominant, co-dominant, intermediate and suppressed), and (iii) the lifespan of the trees (Hynynen 1993, Matala et al. 2003). Dead trees and litter (dead organic material from any part of trees) including cutting residues are decomposed. The decomposition rate is controlled by the quality (ash content, carbon/nitrogen ratio) of litter and humus, soil temperature, and soil moisture (Chertov and Komarov 1997).

Management includes regeneration through planting, thinning and selection of the rotation length. In planting, the user provides the initial stand density (for each tree species) and the distribution of seedlings into different size cohorts. Thinning is based on basal area reduction, which is converted into the number of trees to be removed from each cohort. Thinning can be made from above or from below. In the former case, mainly dominant and co-dominant trees representing the upper quartile of the diameter distribution are removed, and in the latter case suppressed and intermediate trees representing the lower quartile of the diameter distribution are removed. Thinning disturbances increase litter input to the soil in the form of logging residues, thereby increasing nitrogen availability after litter decomposition.

Trees removed in thinning and final cut are converted to saw logs and pulp wood. The minimum diameter was 15 cm for saw logs and 6 cm for pulp wood. Stems that were smaller than these dimensions were treated as residue wood. The amount of different timber assortment is calculated based on empirical tables (Snellman, V., Finnish Forest Research Institute, unpublished) which provide the amount of saw logs, pulp wood and logging residue as a function of the breast height diameter and tree height. Moreover, the model calculates the total C stock in trees (C in above- and below-ground biomass), the C stock in soil and the C content in harvested timber.



**Table 1.** Structure and properties of FinnFor model (for more details see Kellomäki and Väisänen 1997).

<b>Main modelling objectives and management options</b>	
Modelling objectives	Long-term dynamics of forest ecosystem as controlled by environmental conditions (climate, soil) and management; boreal forests
Management options	Thinning and final cutting; regeneration (natural regeneration, planting), nitrogen fertilisation, tree species choice (Scots pine, Norway spruce and birch spp.)
<b>Ecosystem structure</b>	
Stand structure	Cohorts of single tree species in terms of number, age, height and diameter
Tree structure	Foliage, branches, stem, coarse roots and fine roots
Soil structure	Litter on soil, soil organic matter (humus), mineral soil profile down to selected depth and divided up to ten soil layers
<b>Model structure</b>	
Model type	Mechanistic, deterministic
Time step	Hourly for physiological processes, annual for ecological and management processes
Environmental control by atmosphere	Radiation, temperature, precipitation, air humidity, wind speed, CO <sub>2</sub> concentration
Environmental control by soil	Soil moisture, soil temperature, available nitrogen
<b>Functioning of the model processes</b>	
<u>Tree and stand level processes</u>	
Photosynthesis	Biochemical model for photosynthesis driven by atmospheric and soil factors listed above
Autotrophic Respiration	Day respiration and maintenance respiration controlled by temperature, growth respiration as a fraction of photosynthesis allocated to growth
Stomatal conductance	Controlled by radiation, temperature, air humidity, CO <sub>2</sub> concentration, soil temperature and moisture (the Jarvis type)
Transpiration	Penmann-Montheith type
Mortality and litter	Probability of death of an individual tree and stand level self-thinning, organ specific turnover rates for foliage, branches, coarse roots and fine roots
Seasonality	Temperature controlled dynamics in photosynthetic capacity, respiration and phenology
<u>Soil processes</u>	
Temperature	Soil temperature controlled by radiation balance and physical properties of soil
Water	Soil moisture controlled by precipitation, evapotranspiration and outflow of water
Nitrogen	Available nitrogen controlled by litter fall, decomposition of litter and humus and uptake of nitrogen by trees
Carbon	Dynamics controlled by heterotrophic losses under the control of soil moisture and temperature and quality of litter
<b>Main model outputs</b>	
Water balance	Precipitation, evaporation, transpiration, runoff (surface and groundwater), available soil water
Nitrogen cycle	Uptake, deposition, litterfall, decomposition, available nitrogen
Carbon balance	Gross primary production, autotrophic respiration, heterotrophic respiration, carbon in trees and soil
Structure and properties of stands and harvested timber	Trees and stand structure as described above. Harvested timber (logs, pulp), carbon in harvested timber

*Performance of the model.* The FinnFor model has been parameterised based on long-term forest ecosystem data and climate change experiments (Kellomäki et al. 2000), and successfully evaluated with regard to (i) model validation against growth and yield tables (Kellomäki and Väisänen 1997), (ii) measurements of short-term stand-level fluxes of water and C at intensively studied sites by means of the eddy covariance method, along with (iii) model evaluation against five other process-based models (Kramer et al. 2002) and (iv) measurements of the growth history of trees in thinning experiments (Matala et al. 2003). In addition, hydrological and nitrogen cycles included in the model have recently been validated by Laurén et al. (2005) against long-term monitoring data representing these processes; a close correlation between the simulated and measured outflow of water and nitrogen from the watershed was found. Similarly, Venäläinen et al. (2001) demonstrated a close correlation between the measured and simulated values of snow accumulation and soil frost.

The performance of the model has been tested against the measurements of growth of trees in long-term thinning experiments of Scots pine, Norway spruce and birch stands (see Matala et al. 2003). Moreover, parallel simulations have been carried out by Matala et al. (2003) and Briceño-Elizondo et al. (2006) for the Finnish conditions between FinnFor and Motti, a statistical growth and yield model which was developed by Hynynen et al. (2002). The Motti model is based on tree growth data from a large number of sample plots (forest inventories) and forms a growth modelling part of a large-scale forestry scenario model MELA (Siitonen et al. 1996, Redsvén et al. 2004). All these studies demonstrate that FinnFor provides realistic predictions and that it is capable of simulating the growth and development of trees stands under the current climate and using different thinning schedules in a similar way than typical growth and yield models (statistical models). Moreover, climate sensitivity analyses have been carried out with FinnFor to evaluate the effects of climate variation on forest growth (Lindner et al. 2005, Briceño-Elizondo et al. 2006).

### 2.3.2 Wood Products Model (Paper IV)

The simulations on timber production provided by FinnFor model were further used as inputs into the WPM to calculate the C resilience times within different wood product categories. The WPM tracks the flow of C in harvested timber through production processes and its subsequent storage in wood-based commodities until it is released again to the atmosphere. The model operates on a yearly time step and requires input files containing information about the C content in the harvested timber (in Mg C), separated into different assortments. The C contained in the assortments is assigned to different production lines (e.g. sawmill industry, plywood industry, pulp and paper industry) or used as fuel wood. The products are assigned to different lifespan categories and after the end of the product lifecycle, C is assigned to recycling, landfill deposition or burnt for energy production. The structure of the WPM as applied in this study follows closely the conception and parameterisation from Karjalainen et al. (1994) and Eggers (2002). The parameters for those studies were estimated based on data from the Finnish yearbooks of forest statistics and on an extensive parameterisation scheme for Europe based on FAOSTAT data bases (FAO 2000, Eggers 2002).

### 2.3.3 Additive multi-criteria utility model (Paper IV)

The simulations from the FinnFor and wood product models provided input data for the multi-criteria analysis of forest management alternatives. A multi-attribute utility model was used to calculate a utility index for optional management strategies at management unit level. First, utility at stand level is calculated for each stand and each treatment with regard to a set of management objectives, each decomposed into decision criteria. The utility of stand treatment alternative (i) applied to stand (o) is calculated with Eq. (2),

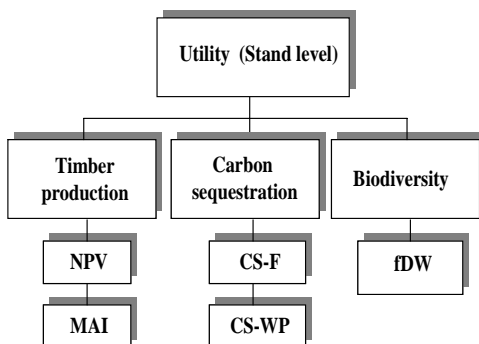
$$U(sl)_{io} = \sum_{j=1}^n w_j U_{ioj} \quad (2)$$

where  $U(sl)_{io}$  is calculated from partial utilities  $U_{ioj}$ ,  $w_j$  is the relative weight (i.e., importance) of the partial objective (j) ( $j=1, \dots, n$ ). The weights have to be non-negative and sum up to 1. The utility from partial objectives is calculated from preference functions which measure the preferentiality of each alternative (i) with regard to (k) decision criteria (Eq. (3)),

$$U_{ioj} = \sum_{k=1}^{m_j} v_{jk} P_{jk}(x_{iojk}) \quad (3)$$

where  $P_{jk}(x_{iojk})$  is the preference for the performance of alternative (i) with regard to criterion (k) of partial management objective (j) calculated by means of preference functions from the value of objective variable  $x_{iojk}$  in management alternative (i) of stand (o), and  $v_{jk}$  the relative weight (i.e., importance) of the criterion (k) ( $k=1,2,\dots,m$ ) regarding the partial objective (j). The weights have to be non-negative and add up to 1.

Partial management objectives used were: timber production (TP), C sequestration (CS) and biodiversity (BD). Each of these management objectives is broken down into decision criteria (**Figure 5**). The net present value (NPV) and the mean annual timber increment (MAI) over the simulation period were used to characterise timber production. The C sequestration criteria, the C stock in the forest ecosystem (CS-F) and in wood products (CS-WP), were calculated as an average stock over the 100-year planning period ( $\text{Mg C ha}^{-1}$ ). Biodiversity was represented by the amount of average annual fresh deadwood.



**Figure 5.** Decision hierarchy used to calculate the utility of treatment programmes at the stand level. NPV = net present value ( $p=0.02$ ) [ $\text{€ ha}^{-1}$ ], MAI = mean annual timber increment over 100 years [ $\text{m}^3 \text{ha}^{-1}$ ], CS-F = mean carbon storage in the forest (above- and below-ground tree biomass, carbon in the soil) over 100 years [ $\text{Mg C ha}^{-1}$ ], CS-WP = mean carbon storage in wood products over 100 years [ $\text{Mg C ha}^{-1}$ ], fDW = average annual fresh deadwood [ $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ ].

The preference functions used in this study were defined in a generic approach and followed fairly intuitive considerations (**Figure 5, IV**). Whenever possible a linear preference relationship between the minimum and maximum criterion values from all simulations was used. For example, for NPV a decreasing marginal preference at high levels of NPV was assumed.

In calculating the total utility of a management plan, constraints and objectives at the unit level have to be considered. In this example, two criteria at the unit level were defined. A minimum amount of harvested timber per decade ( $TH_{\min}$ ) was required, indicating the minimum level of timber harvests required to cover general costs and secure financial liquidity of the FMU. The even flow of timber harvests ( $TH_{\text{flow}}$ ) represented by the coefficient of variation of decadal timber harvests was used to indicate the regularity of timber flows. The utility component at the unit level for a given management plan (I) ( $U(\text{ul})_I$ ) is calculated with Eq. (4),

$$U(\text{ul})_I = p_1 \cdot A_{TH_{\min}} + p_2 \cdot A_{TH_{\text{flow}}} \quad (4)$$

$$\sum_{m=1}^2 p_m = 1$$

where  $A_{TH_{\min}}$  measures the achievement with regard to the minimum required decadal timber harvest constraint,  $A_{TH_{\text{flow}}}$  the corresponding achievement index for the requirement of an even harvest flow over the planning period (**Figure 6, IV**). The coefficients  $p_1$  and  $p_2$  indicate the relative importance of the criteria.

Total utility  $U_I$  of a management plan is calculated using stand level and unit level components (Eq. 5),

$$U_I = w_1 \cdot \sum_{o=1}^{1018} a_{rel,o} \cdot U(\text{sl})_{i,o} + w_2 \cdot U(\text{ul})_I \quad (5)$$

$$\sum_{r=1}^2 w_r = 1$$

where the coefficients  $w_r$  represent the relative importance of each component. The stand level utilities are aggregated by an area weighted average over all stands of the FMU.

## 2.4 Computations and analyses

### 2.4.1 Analyses on the effects of management and climate scenarios on timber production, carbon stocks in forest ecosystem and carbon stocks in harvested timber (Papers I-III)

In this work, the effects of management and climatic conditions on timber production, carbon stocks in forest ecosystem and carbon stocks in harvested timber were studied based on the use of representative stands in simulations instead of all individual stands of the management unit (Papers I-III). This was done to reduce the number of simulations. These

representative stands were selected from the FMU using the following steps. All 1018 stands were first classified into groups with the same dominant tree species (Scots pine, Norway spruce or silver birch), age class (10 year intervals) and soil fertility type (OMT, MT, VT). Then, from each group a typical stand representing the normal growing situation was selected. A total of 42 representative stands were selected for simulations. The number of trees in each representative stand was then distributed evenly over three cohorts assigning to the first cohort the mean height and DBH from inventory. For the second and third cohorts those values were increased by 15% and decreased by 15%, respectively. In each representative stand the initial mass of organic matter in the soil was assumed to be 70 Mg ha<sup>-1</sup>. The stands were simulated over 100 years using various management and climate scenarios presented in sections 2.2.2 and 2.2.3. The data obtained from simulations (timber yield, C stock in trees, C stock in soil, C in harvested timber) for the 42 representative stands were then applied to all represented stands.

In this work, the growth of stem wood and timber yield (saw logs and pulp wood) were analysed in order to indicate the impacts of climate change and forest management on them based on the original forest structure of the management unit (Paper I). The total stem wood growth and timber yield were calculated for the 100-year simulation period (m<sup>3</sup> ha<sup>-1</sup>) by accumulating the annual rates of growth and yield over the period. In order to indicate the effects of the forest management regimes and climate change on C stocks at the management unit level over the 100-year simulation period, C stocks in the forest ecosystem based on the original forest structure were also analysed (Paper II). In this context, the C stock in trees (C in above- and below-ground biomass) and the C stock in soil were calculated in terms of the mean C storage over the simulation period (Mg C ha<sup>-1</sup>). In addition, the total C stock in harvested timber (Mg C ha<sup>-1</sup>) was calculated.

The sensitivity of timber yield (saw logs and pulp wood) (m<sup>3</sup> ha<sup>-1</sup>) and C stocks in forest ecosystem (Mg C ha<sup>-1</sup>) were also analysed for the 100-year simulation period by applying different initial forest landscape structures (in terms of age class distributions), management regimes and climate scenarios (current climate and HadCM2 climate change scenario) concurrently (Paper III). The following age class groups were used in analyses: 0-20 year old saplings stands, 21-40 year old thinning stands, 41-70 year old thinning stands, and 70-100 year old stands. Then, four different age class distributions were created depending on how the area of the management unit was assigned to each of the groups (**Table 2**): (A) distribution dominated by intermediate age classes (normal distribution), (B) distribution dominated by no single age class (equal distribution), (C) distribution dominated by young age classes (left-skewed distribution), and (D) distribution dominated by old age classes (right-skewed distribution).

**Table 2.** Age class distributions used and percentage of area occupied by each of the age class groups (sapling stands, young stands ready thinnings, older thinning stands and stands at clear-cut age) and species taking as a reference the original area occupied by each species<sup>a</sup> (Norway spruce 933 ha, Scots pine 412 ha and silver birch 106 ha).

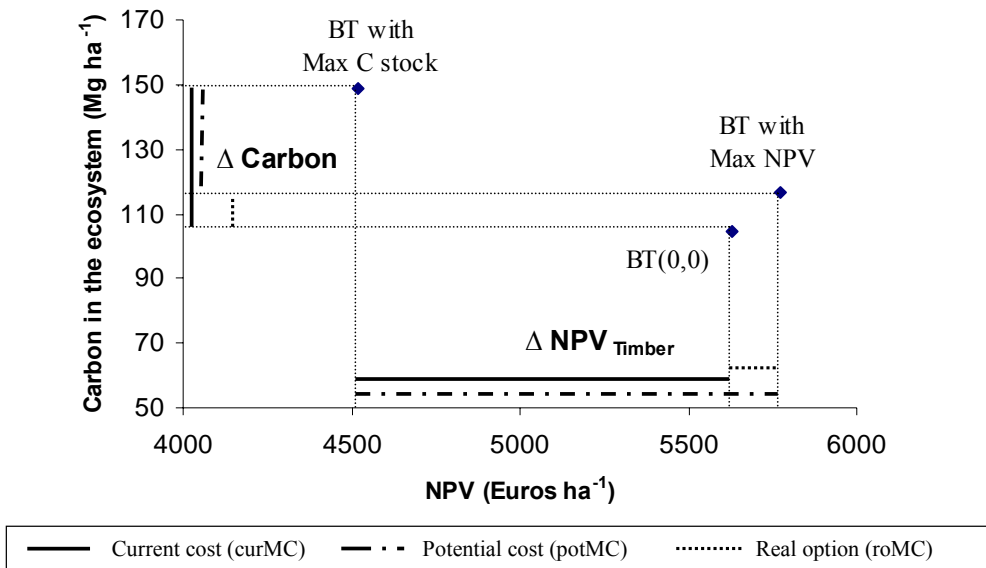
Age groups	Age	Age class distributions			
		A Normal	B Equal	C Left-skewed	D Right-skewed
Sapling stands (0-20 years)	0-10	12.5	12.5	25	5
	11-20	12.5	12.5	25	5
	<b>Total (%)</b>	<b>25</b>	<b>25</b>	<b>50</b>	<b>10</b>
Young thinning stands (21-40 years)	21-30	15	12.5	12.5	7.5
	31-40	15	12.5	12.5	7.5
	<b>Total (%)</b>	<b>30</b>	<b>25</b>	<b>25</b>	<b>15</b>
Older thinning stands (41-70 years)	41-50	10	8.3	5	8.3
	51-60	10	8.3	5	8.3
	61-70	10	8.3	5	8.3
<b>Total (%)</b>	<b>30</b>	<b>25</b>	<b>15</b>	<b>25</b>	
<b>Stands at clear-cut age (&gt;70 yr)</b>	<b>Total<sup>b</sup> (%)</b>	<b>15</b>	<b>25</b>	<b>10</b>	<b>50</b>

<sup>a)</sup> For example: When calculating the area for the normal age class distribution for Scots pine it is necessary to multiply the total original area for the species (412 ha) by the percentage presented for each of the age classes i.e. 0-10 years old (12.5%) giving an area of 51.5 ha for Scots pine for this age class in the normal distribution (A).

<sup>b)</sup> Because not all the species reach an age of 100 years, the area corresponding to the group (>70 years old) is divided equally to the age classes present in the group.

Furthermore, the income and costs (e.g. planting and other regeneration costs) were included in the analysis in order to calculate the NPV of timber production for the management unit including the discounted value of standing stock at the end of the simulation (Papers I, III-IV). The discount rates used for calculating NPV were 0%, 1%, 3% and 5% in Papers I and III, while in Paper IV a discount rate of 2% was used. For calculating the opportunity cost in Paper I only a discount rate of 3% was used, with the aim of identifying the most preferable management regime under given socio-economic constraints (timber production costs and revenues) and the climate scenarios (see Paper III). In the economic calculations, the prices of different timber assortments per species and costs of the regeneration operations (soil preparation and plantation per species) were the average prices for the period 1990-2000 (Finnish Statistical Yearbook of Forestry 2001) (Papers I, III-IV).

Moreover, based on the NPV and mean C stocks in the ecosystem over the 100-year period, the cost of C sequestration by C sink enhancement was also calculated in terms of € per Mg of C (Paper III). In these calculations, the C stocks in wood-based products were excluded, and costs were estimated assuming exogenous prices and costs. This is an indirect pricing method based on the opportunity cost, which the increase in the C sequestration may result due to the reduction in timber production. Thus, the discounted present value of opportunity costs were divided by the enhancement of C storage in order to analyse the opportunity costs under varying preferences between the timber production and the C sequestration. **Figure 6** shows a typical scatter plot of C sequestration and NPV from timber production.



**Figure 6.** Scheme for the calculation of the cost of carbon (C) sequestration with the NPV and C stock corresponding to the management that gives the maximum NPV, the management that gives maximum C stock and the business-as-usual management (Basic Thinning, BT(0,0)).

Based on the opportunity costs, the marginal cost for C sequestration was calculated in three ways following the principles presented in **Figure 6**:

- *Potential marginal cost of carbon sequestration (potMC)* refers to the differences in the C stock and in NPV of timber representing the management regimes maximising the C stock and NPV, respectively.
- *Current marginal cost of carbon sequestration (curMC)* refers to the differences in the C stock and in NPV of timber production, when management shifts from the current management to management that aims to maximise the C stock.
- *Real option marginal cost of carbon sequestration (roMC)* refers to the differences in the C stock and in NPV when management shifts from the current management to management that aims to increase both the C stock and NPV of timber production. This option may not be always possible.

#### 2.4.2 Optimisation of forest management under changing climatic conditions (Paper IV)

The amount of harvested timber and C stocks in the ecosystem (based on FinnFor simulations for Papers I and II) along with the C stock in wood products (based on WPM simulations for Paper IV) provided input data for the multi-criteria analysis of forest management alternatives under different climate regimes. In this study three objective

scenarios were analysed to represent contrasting views on forest management objectives. Two scenarios had a clear focus on a single objective, timber production (MaxTP) and C sequestration (MaxCS) respectively. The third scenario (multi-objective; MO) assumed an equal importance of all management objectives (timber production, C sequestration and biodiversity). All parameters of the utility model (Eqs. 2-5) used in the analysis are presented in Tables 2 and 3 in Paper IV. The aggregated utility from stand level performance was considered more important than the achievement with regard to FMU level constraints. In the objective scenarios maxTP and MO the unit level criteria were assigned equal importance, in maxCS the even flow of timber harvests was not considered.

In this study a utility function (Eq. 5) was maximised by a heuristic which consists of random and direct search components. To start the optimisation process, one treatment schedule was selected randomly for each stand to obtain an initial management plan. This was repeated 500 times. The five random management plans with the highest overall utility were used as a starting point to continue with a direct search procedure. One stand at a time was examined to see whether another treatment increased total utility. As an additional constraint at stand level the utility of a treatment had to be at least as good as the business-as-usual stand management (BT(0,0)) to replace another treatment in the optimised plan. The rationale for this constraint is that the trade-off of utility at the stand level, where actually the value added of forest management is generated, for improved achievement values with regard to level constraints has to be limited.

Once all the treatment plans of each stand were revised in this way, the process was repeated several times (i.e. cycles). In this study 15 cycles were used and executed for each of the five initial random plans. The optimisation stopped either after the last specified cycle or when no improvement in utility was achieved over two consecutive cycles. To see whether the optimisation was effective, a user-specified proportion of the treatment plans was replaced randomly after termination to check the specificity of the optimised plans. In its core features this optimisation procedure is similar to the HERO approach as presented by Pukkala and Kangas (1993). In Finland, HERO has been used for more than a decade for both non-spatial and spatial optimisation problems.

Management plans were generated for each of the three objective scenarios (maxCS, maxTP, MO) under the climate scenarios (current, ECHAM4, HadCM2). To indicate the within scenario variability regarding the share of selected stand treatment programs (STPs), five optimised plans were produced for each combination of objective and climate scenario (3 objectives x 3 climate scenarios). For each objective/climate combination the solution with the highest overall utility was chosen as the best management plan. In contrast to the optimised plans, the objective functions for maxCS, maxTP and MO were also calculated for plans consisting of one specific STP exclusively. First, these plans were compared with the optimised plans to identify the potential of mixing STPs over the FMU. Second, the assignment of STPs in the optimised plans was compared among the different scenarios. Third, to indicate the potential of considering climate change in the optimisation, each management objective scenario was analysed by applying the management plan optimised for current climate to the climate change scenarios.



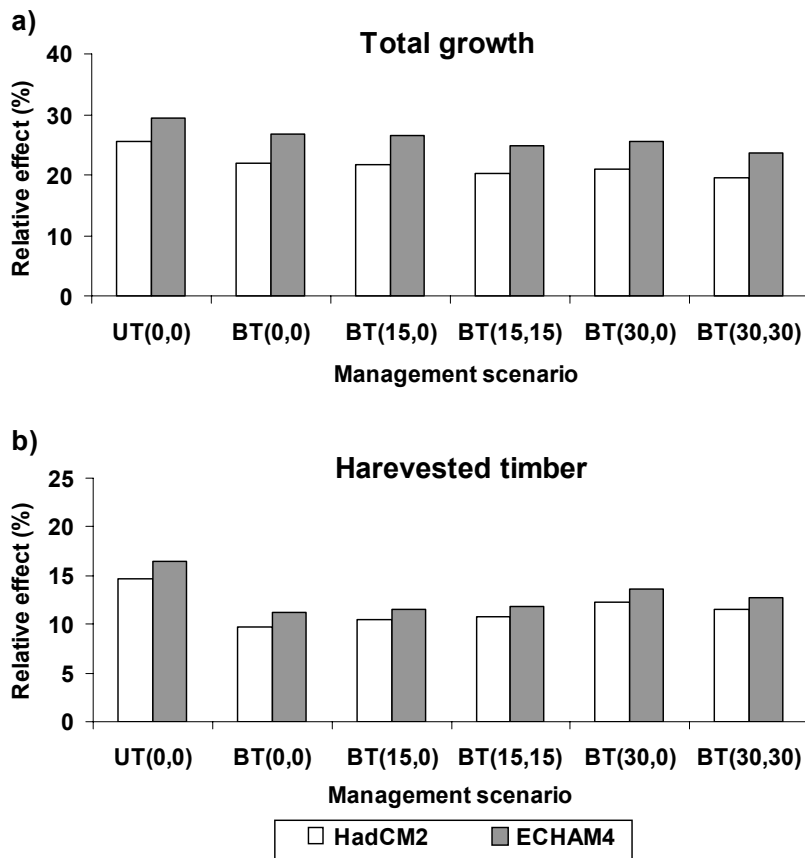
### 3 RESULTS

#### 3.1 Effects of management and climate scenarios on timber production (Paper I)

*Management under current climate.* Over the FMU, the total growth of stem wood in the unthinned regime (UT(0,0)) was  $864 \text{ m}^3 \text{ ha}^{-1}$ , of which one third was lost through mortality (34%,  $293 \text{ m}^3 \text{ ha}^{-1}$ ) (Table 3, I). Although the total growth was 37% higher than under the Basic Thinning (BT(0,0)), the timber yield was 24% lower (BT(0,0)  $619 \text{ m}^3 \text{ ha}^{-1}$ ). In the latter case, the amount of deadwood was small (5%,  $34 \text{ m}^3 \text{ ha}^{-1}$ ) as was the case also for other thinning regimes (1-6%). It was also found that an increase of 15% and 30% in the upper limit of the basal triggering thinning (BT(15,0), BT(30,0)) increased the total growth and timber yield compared to that under BT(0,0). This tendency was further enhanced if the basal area remaining after thinning was also increased; i.e. in thinning regimes BT(15,15) and BT(30,30). The increased growth was clearly related to the increased stocking throughout the rotation, with an increase ranging from 2% under BT(15,0) up to 11% under BT(30,30) compared to BT(0,0).

Similarly to growth, also timber yield tended to increase if thinning was done later than under BT(0,0). Over the entire FMU, the increase in timber yield was 3% and 5% under the thinning regimes BT(15,0) and BT(30,0), respectively, relative to BT(0,0). This tendency was further enhanced if the remaining basal area after thinning was also kept higher than under BT(0,0); i.e. the increases were 6% and 12% for BT(15,15) and BT(30,30), respectively. Although the management regimes were species-specific, the effects of the management on the total growth and timber yield followed the same pattern regardless of tree species (**Table 3, I**). Any increase in timber yield implied correspondingly an increase in the values of NPV, but the values were substantially influenced by the discount rate (see **Table 4, I**). The highest values of NPV were obtained under the thinning regime BT(30,30) if the discount rates 0, 1 and 3% were used. If a discount rate of 5% was applied, the thinning regime BT(0,0) was more profitable than the others due to the earlier thinnings and final cut applied in this regime. Regardless of the discount rate, the lowest values of NPV were obtained in the unthinned regime (UT(0,0)) (**Tables 3 and 4, I**).

*Management under climate change.* The total growth of stem wood for the entire FMU increased clearly under changing climate compared to the current climate (**Figure 7**). Under the HadCM2 climate scenario, the total growth was increased by 20-22% and under the ECHAM4 24-27% depending on the thinning regime. The increase in total growth was slightly higher without thinning than under thinning regimes, but the net growth (excluding mortality) increased similarly for the thinning regimes and the unthinned regime due to the larger mortality observed when no thinning was applied (mortality was on average 36% of the total growth for both HadCM2 and ECHAM4 climate scenarios). When thinnings were applied, the proportion of deadwood ranged from 5% ( $34 \text{ m}^3 \text{ ha}^{-1}$ ) under the current climate to 6% under the climate change scenarios ( $45 \text{ m}^3 \text{ ha}^{-1}$  for HadCM2 and  $48 \text{ m}^3 \text{ ha}^{-1}$  for ECHAM4).



**Figure 7.** Relative effects of climate change scenarios (ECHAM4 and HadCM2) on total growth (a) and harvested timber (b) of all species in the management regimes, taking the current climate as the baseline. See key to the management regimes in Figure 3.

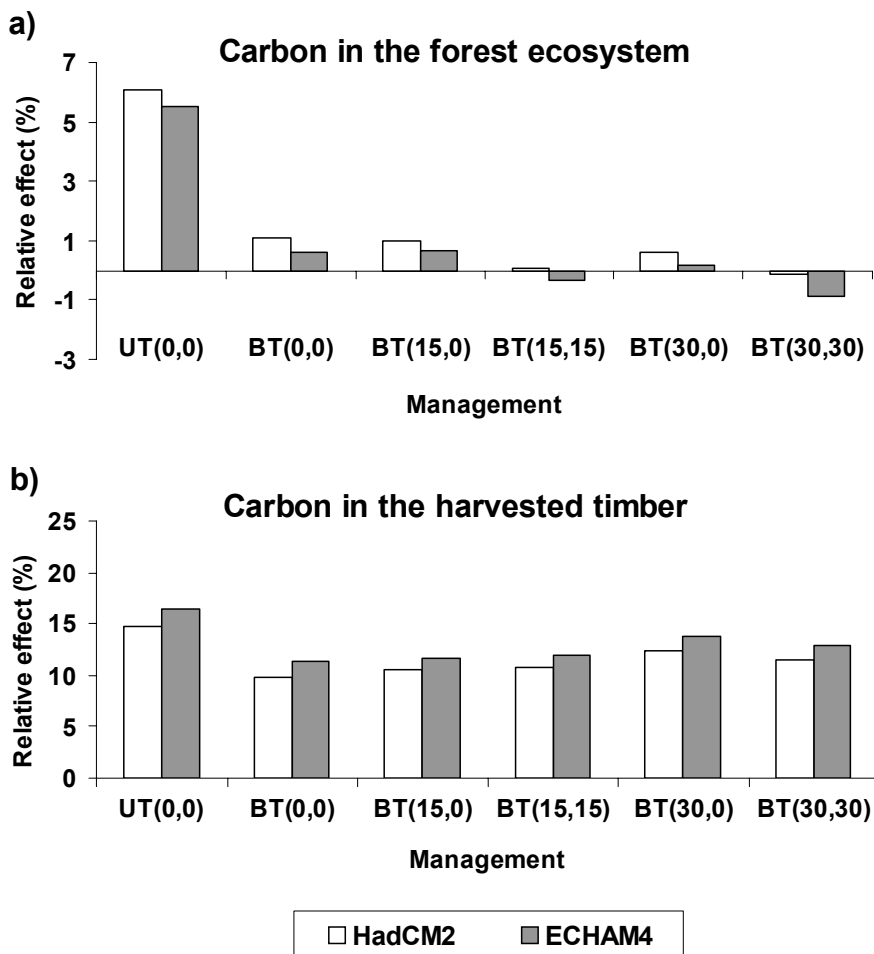
The timber yield increased under the climate change scenarios as did the total growth of stem wood; however the change was smaller. The mean increase, for all the thinning regimes, relative to current climate was 11% for the HadCM2 and 12% for the ECHAM4 climates (**Figure 7**). The increase without thinning UT(0,0) was 15% and 16% for the HadCM2 and ECHAM4 climates, respectively. Both climate change scenarios also tended to trigger thinnings earlier and, thus, increase the number of thinnings. However, the thinning regime affected the timber yield in the same way as under the current climate (**Table 3, I**). Consequently, the timber yield was the highest ( $771 \text{ m}^3 \text{ ha}^{-1}$  for HadCM2 and  $781 \text{ m}^3 \text{ ha}^{-1}$  for ECHAM4) for the thinning regime BT(30,30), with an increase of 14% (HadCM2) and 13% (ECHAM4) relative to BT(0,0). Also under climate change, the NPV increased substantially compared to the NPV under current climate as a result of increasing timber yield. However, the level of impact of climate change on the NPV was dependent on management regime and discount rate levels applied (**Figure 4, I**).

### 3.2 Effects of management and climate scenarios on C stocks in forest ecosystem and C stocks in harvested timber (Paper II)

*Carbon stock in the forest ecosystem.* Under current climate, the average C stock in the forest ecosystem (average of C in trees and C in soil) over 100 years was the largest for the unthinned regime UT(0,0), i.e. 154 Mg C ha<sup>-1</sup> of which 48% was in trees (73 Mg C ha<sup>-1</sup>) and 52% in soil (81 Mg C ha<sup>-1</sup>). Under the Basic Thinning regime BT(0,0), average C stock in the ecosystem was 45% lower than that under UT(0,0). However, the thinning regime had a clear effect on total C stock in the ecosystem (Table 4, II). The increase in the threshold triggering thinning (thinning delayed from that of BT(0,0)) and remaining basal area after thinning, with the consequent increase in stand stocking throughout the rotation, increased the total C stock in the ecosystem. When the upper limit of basal area for thinning was increased by 15% in BT(15,0) and 30% in BT(30,0) thinning regimes, C stock increased by 3% and 6%, respectively, compared to that under BT(0,0). If the remaining basal area after thinning was also increased, C stock in the ecosystem was further enhanced up to 11% for BT(30,30). The management regimes were species-specific, but the effect of different management regimes on the total C stock in the ecosystem followed the same pattern for all species (Table 4, II).

The C stock in trees followed the same pattern as total C stock in the ecosystem but the relative effect of management was larger (Table 4, II). An increase in the thinning threshold increased C stock in trees, especially if the remaining basal area was also increased. The same pattern was observed in the case of C in soil but the relative change was smaller. The increase of C in trees over the entire FMU was a maximum of 21% for BT(30,30) compared to that of 40 Mg C ha<sup>-1</sup> under BT(0,0). C stock in trees for UT(0,0) was 83% higher than that under BT(0,0). The corresponding increase of C in soil ranged from 1% for BT(15,0) to 6% BT(30,30) compared to that of 66 Mg C ha<sup>-1</sup> under BT(0,0). For the unthinned regime, C in soil was 23% higher than that under BT(0,0).

The effect of climate change scenarios on C stock in the forest ecosystem (C in trees plus C in soil) varied within the management regimes. Compared to current climate, C stock in the forest ecosystem over the entire FMU increased slightly for some thinning regimes (excluding unthinned) and decreased for the remainder (**Figure 8**). However, for the unthinned regime UT(0,0) the increase due to climate change was clear, being 5% and 6% for ECHAM4 and HadCM2, respectively. Under changing climate, the thinning regime affected C stock in the forest ecosystem in the same way as in the current climate (Table 5, II). The highest values for C stock in the forest ecosystem were found for UT(0,0), 52% greater than those of BT(0,0). For thinned stands the highest C stock was reached with BT(30,30). On average, the C stock in the forest ecosystem was 10% higher under thinning regime BT(30,30) than that under BT(0,0).



**Figure 8.** Effects of climate change on (a) total C stock in the forest ecosystem (C in trees and C in soil) and (b) C in harvested timber for different management regimes, taking the current climate as the baseline. See key to the management regimes in Figure 3.

Regardless of species and management regime applied, both climate change scenarios showed also a clear increment of C stock in trees (**Figure 4, II**). Compared to the current climate, for different thinning regimes (excluding unthinned) the mean increment of total C stock in trees over the entire FMU was about 8% and 6% for the ECHAM4 and HadCM2 climates, respectively. For unthinned stands the increment was larger, i.e. 16% and 14% for ECHAM4 and HadCM2, respectively. Over the whole FMU, C stock in soil reacted differently to climate change than C stock in trees. Both climate change scenarios showed a clear decrease of C stock in soil compared to that under current climate (**Figure 4, II**). Compared to that under BT(0,0), the mean decrease of C stock in soil over the whole FMU within thinning regimes (excluding unthinned) was about 5% and 3% for the ECHAM4 and

HadCM2 climates, respectively. For unthinned stands, the decrease was smaller, i.e. 4% for ECHAM4 and 1% for HadCM2.

*Carbon stock in the harvested timber.* Under current climate, the total C in harvested timber (saw log and pulp wood) was 96 Mg C ha<sup>-1</sup> in the unthinned regime (UT(0,0)) (**Table 6, II**). This is 24% less than that under BT(0,0), which yielded 126 Mg C ha<sup>-1</sup> over the rotation. C stock in harvested timber tended to increase if thinning was done later than that under BT(0,0). The increment of C stock in harvested timber was around 3% and 5% under thinning regimes BT(15,0) and BT(30,0) compared to that under BT(0,0). This tendency was further enhanced if the remaining basal area in the stand after thinning was also kept higher than in BT(0,0). The thinning regimes BT(15,15) and BT(30,30) increased the total C stock in harvested timber by 6% and 12%, respectively compared to that of BT(0,0). Thus, the largest amount of C in harvested timber was found under the thinning regime BT(30,30) (**Table 6, II**).

Regardless of species and management regimes, both climate change scenarios also showed an increase of C in harvested timber relative to current climate conditions, the increment being higher in the ECHAM4 than in the HadCM2 climate. For the whole FMU, the mean increase for the thinned stands was 11% for the HadCM2 and 12% for the ECHAM4 climate compared to the current climatic conditions (**Figure 5, II**). Under the unthinned regime UT(0,0), the corresponding increase of C stock in harvested timber was larger than for the thinning regimes, ranging between 15% and 16% for the HadCM2 and ECHAM4 climate, respectively. Under the changing climate, the thinning regime affected the C stock in the harvested timber in the same way as in the current climate, with the highest values for thinning regime BT(30,30) regardless of the tree species (**Table 7, II**).

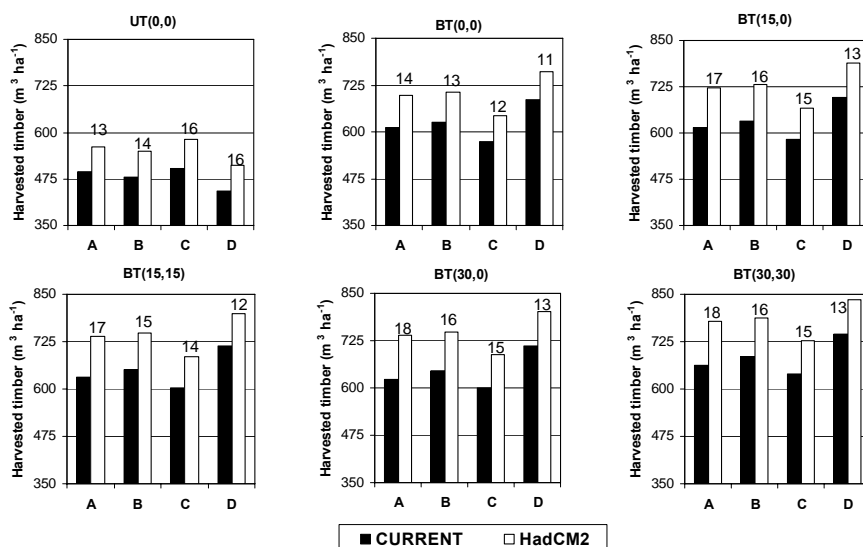
### **3.3 Effects of forest structure on timber production and C stocks under changing management and climatic conditions (Paper III)**

*Effects of forest dynamics and forest structure on timber production and C stocks under Basic Thinning regime BT(0,0) and changing climate.* Under the *current climate*, the normal and the equal age class distributions produced a more balanced timber harvest over time, whereas the left-skewed distribution (forests dominated by sapling stands) provided most of the timber during the latter years of the simulation. The right-skewed distribution (forests dominated by mature stands) yielded most of the timber during the early phase of the simulation as one may expect (**Figure 6, III**). Consequently, this initial age class distribution also gave the highest NPV for timber produced over the rotation. The same patterns held for the *changing climate*, but the timber yield and its NPV were larger than those under the current climate.

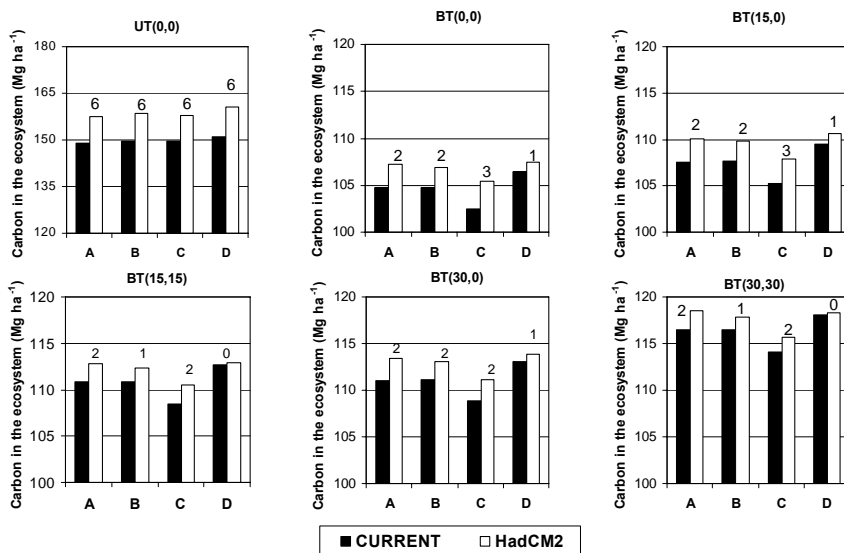
Under the *current climate*, the average C stock in the ecosystem was the smallest in the latter stages of the simulation period (the years 2081-2100) when the initial age class distribution to the left was applied in the simulations (**Figure 7, III**). During the same period, the C stock was the largest when the right-skewed distribution was applied at the start of the simulation. The application of equal and normal distributions gave a larger C stock than the left-skewed distribution, but even in these cases the C stock remained smaller than when the right-skewed distribution was applied. The *changing climate* modified these patterns and, for example, in the latter stages of the simulation period (2081-2100) the C stock was slightly smaller for the right-skewed initial distribution than for other initial

distributions (**Figure 7, III**). In general, climate change increased the total C stock in the ecosystem regardless of the initial age class distribution.

*Effects of forest structure on average timber production and C stocks under changing management and climate.* The average timber yield per hectare over the 100-year simulation period was affected by both the initial age class distribution and management. The management also had a clear effect on the C stock in the ecosystem. However, C stocks were only slightly influenced by the initial age class distribution. When the *current climate* and BT(0,0) were used, the largest amount of timber yield and C stock in the ecosystem ( $687 \text{ m}^3 \text{ ha}^{-1}$ ,  $106 \text{ Mg C ha}^{-1}$ ) were obtained when the initial forest landscape was dominated by old stands mature for clear-cutting (right-skewed distribution). The smallest values ( $573 \text{ m}^3 \text{ ha}^{-1}$  of timber and  $103 \text{ Mg C ha}^{-1}$ ) were obtained when applying the left-skewed initial age class distribution. Under the *changing climate*, these patterns remained, but the timber yield increased up to 11-18% (**Figure 9**) and the C stocks up to 1-6% (**Figure 10**) depending on the management regime and the initial landscape structure. When comparing the different management regimes the results showed that regardless of the initial age class distribution any increase in the thinning threshold (i.e. BT(15,0) and BT(30,0)) tended to increase the timber yield, the NPV and the C stocks. This tendency was further enhanced if the remaining basal area after thinning was also kept higher than under BT(0,0); i.e. BT(15,15) and BT(30,30). Both the timber yield and the NPV were the smallest in the unthinned regime (**Figure 9, III**). On the contrary, the C stocks in the forest ecosystem were the highest for UT(0,0), being 45% larger than under BT(0,0).

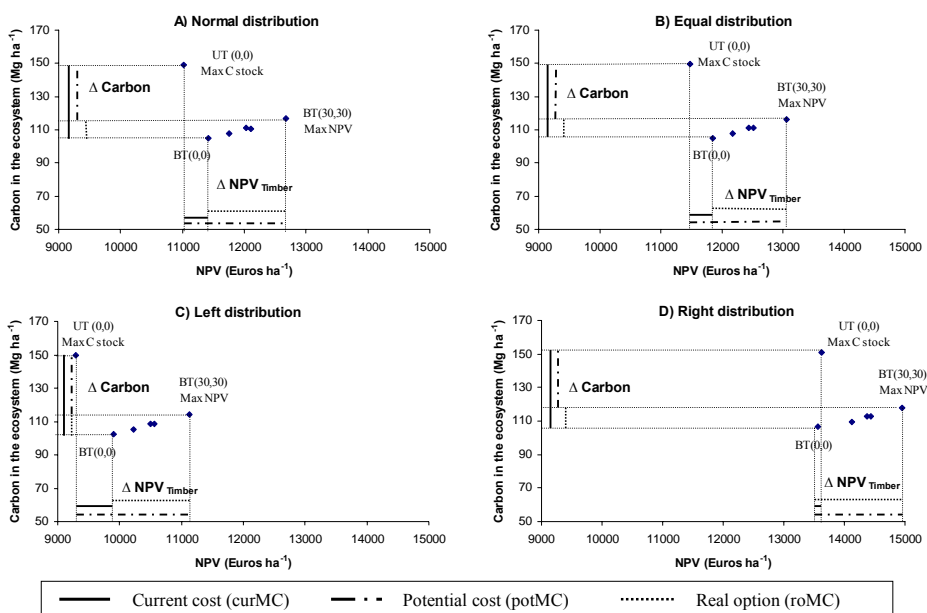


**Figure 9.** Harvested timber over 100 years for four different initial age class distributions using six different management regimes under current (CRU) and changing climate (HadCM2). The numbers given in the figures reflect the increase (%) of harvested timber under changing climate (HadCM2) compared to that under current climate (CURRENT). The distributions used were: (A) normal distribution, (B) equal distribution, (C) left-skewed distribution and (D) right-skewed distribution.



**Figure 10.** Carbon in the ecosystem over 100 years for four different initial age class distributions using six different management regimes under current (CRU) and changing climate (HadCM2). The numbers given in the figures reflect the increase (%) of harvested timber under changing climate (HadCM2) compared to that under current climate (CURRENT). The distributions used were: (A) normal distribution, (B) equal distribution, (C) left-skewed distribution and (D) right-skewed distribution.

In this study, it was not possible to simultaneously achieve the maximum timber production and the maximum C stock in the forest ecosystem. The largest timber production was obtained under the thinning regime BT(30,30) regardless of the climate scenario and the initial age class distribution applied, whereas the management without any thinning (UT(0,0)) maintained the largest C stocks in the ecosystem during the simulation (see **Figures 9 and 10**). However, it was found that it is possible to increase both the amount of C stock in the ecosystem and timber production (and its NPV) at the same time compared to the possibilities provided by BT(0,0) (see **Figure 11**). For example, an additional 32.2 Mg C to 35.5 Mg C ha<sup>-1</sup> would be stored in the forest ecosystem (depending on the initial landscape structure used) if the unthinned management UT(0,0), maximising C stock, was preferred under the *current climate*, instead of the thinning regime BT(30,30) that maximises timber production. This would be done with a potential marginal cost (**potMC**) of 32 to 41 € Mg<sup>-1</sup> depending on the initial landscape structure applied (**Table 3, III**). Under the current marginal cost (**curMC**) approach, the shift from BT(0,0) to unthinned regime UT(0,0) under the *current climate* allows the enhancement of the C sink between 44.2 and 47 Mg C ha<sup>-1</sup> depending on the initial age class distribution used. In **potMC** and **curMC** approaches, the additional C that can be stored due to the use of the unthinned regime UT(0,0) was higher under the *changing climate*. The costs were also slightly higher than those under current climate (**Table 3, III**). Using the real option approach (**roMC**), an increase in average C stock in the ecosystem (between 11 and 12 Mg C ha<sup>-1</sup>) depending on the initial age class distribution used can be obtained when shifting from thinning regime BT(0,0) to BT(30,30) without any loss of NPV regardless of the climate scenario applied.



**Figure 11.** Relationships between carbon (C) in the ecosystem and net present value (NPV) of timber harvests (discounted rate of 1%) for six different management regimes assuming current climate (CRU) scenario for four different initial age class distributions: A (normal); B (equal); C (left-skewed) and D (right-skewed).

### 3.4 Optimisation of forest management under changing climatic conditions (Paper IV)

*Application of same treatment (STP) for all stands.* Regardless of the climate scenario applied, the highest amount of timber harvested and also the highest NPV were found when thinning regime BT(30,30) was used over the entire FMU. This STP allowed a higher timber stocking and later thinnings than BT(0,0) resulting in a higher proportion of logs. As a consequence, BT(30,30) produced the highest amount of C in wood products due to the long-lived nature of products obtained from saw logs. The maximum amount of C stock in the forest ecosystem was found in the unthinned regime (UT(0,0)). Moreover, the Basic Thinning regime BT(0,0) always gave less NPV than all the other thinned STPs, (Appendix Table 1, IV).

*Optimised management plans.* Five optimised management plans were generated for each of the nine objective/climate combinations (3 objective x 3 climate scenarios). Chi<sup>2</sup> tests on the shares of STP by area yielded no significant differences within the objective/climate combinations ( $\alpha = 0.05$ ), indicating that despite the random initial conditions, the optimisation procedure was clearly converging towards scenario-specific optima. In **Table 3** the plans with the highest total utility are shown. For a given climate scenario the optimised solutions (shares of STP by area) differed substantially between the management objective scenarios (chi<sup>2</sup> test significant at  $\alpha = 0.05$ ). The results under the climate change scenarios contrasted somewhat to the results under current climate. A

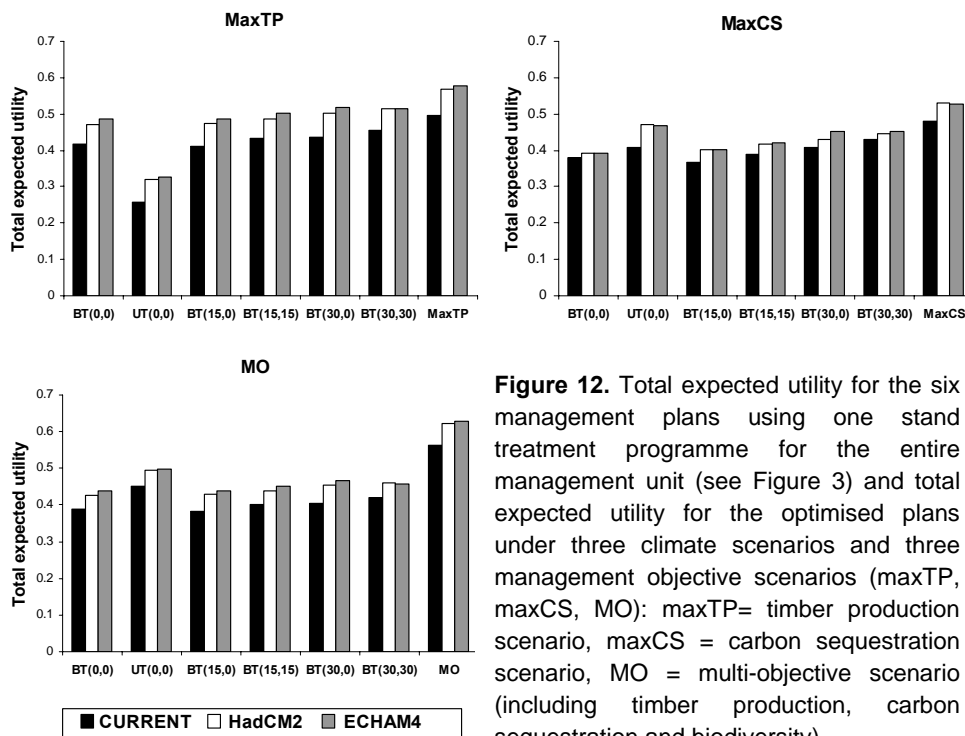


generally observed pattern in all objective scenarios was that under climate change the share of some STPs increased compared to BT(0,0). Those STPs allowed a higher stand stocking over the rotation and later thinnings and final cutting. Chi<sup>2</sup> tests on differences in the share of STPs between climate scenarios within objective scenarios yielded significant differences ( $\alpha = 0.05$ ).

The aim of the optimisation was to maximise aggregated preferences regarding various criteria. The involved trade-offs become apparent when comparing the criteria values as well as the resulting utility values of the optimised management plans (see **Table 4** and **Figure 12**) with the results of the plans implementing the same STP for the entire FMU (**Table 5, IV**). For instance, the use of BT(30,30) for all stands of the FMU generated a higher NPV than the optimised solution of the maxTP objective scenario. However, regardless of the climate and objective scenarios used, the optimal plans always performed better on the unit level constraints and generated higher total utility than the application of one STP for the entire FMU. The relative increase in total utility of optimised plans due to climate change differed somewhat between the objective scenarios. For maxTP the maximum increase was 16.8% (ECHAM4), for maxCS it was 9.9% (HadCM2), and for MO 11.3% (ECHAM4). This pattern was consistent with the results observed with the management plans relying on only one specific STP.

**Table 3.** Distribution of stand treatment programmes (STP) over stands (ha per STP) in optimised management plans for all objective/climate scenario combinations. MaxTP = timber production objective, maxCS = carbon sequestration objective, MO = multi-objective scenario (timber production, carbon sequestration, biodiversity). The plans with the highest total utility are shown.

Objective scenario	Climate scenario	Hectares per stand treatment programme					
		BT(0,0)	UT(0,0)	BT(15,0)	BT(15,15)	BT(30,0)	BT(30,30)
maxTP	Current	167	72	454	171	290	296
	ECHAM4	69	220	406	37	398	321
	HadCM2	124	190	214	31	507	385
maxCS	Current	66	650	117	82	150	386
	ECHAM4	9	671	106.6	93	215	357
	HadCM2	11	669	118	31	236	386
MO	Current	64	876	268	16	108	119
	ECHAM4	2	835	186	30	299	98
	HadCM2	0	885	145	0	357	64



**Figure 12.** Total expected utility for the six management plans using one stand treatment programme for the entire management unit (see Figure 3) and total expected utility for the optimised plans under three climate scenarios and three management objective scenarios (maxTP, maxCS, MO): maxTP= timber production scenario, maxCS = carbon sequestration scenario, MO = multi-objective scenario (including timber production, carbon sequestration and biodiversity).

*Potential benefits of adaptive management.* The optimised management plans for current climate were also used under the two climate change scenarios (ECHAM4 and HadCM2) and the results compared with the findings of plans specifically optimised for these two climate change scenarios. This was done in order to analyse how a management plan optimised for current climate performed under conditions of climate change. Using the plan for current climate under climate change scenarios decreased utility at both the stand and management unit level when compared to the plan optimised for climate change (**Table 4**). However, for some of the individual criteria the solution for current climate gave even higher values than the specific optimal solution for climate change conditions. Overall, due to the assumed trade-off relationship between stand level and unit level utility components, the use of an optimised management plan for a specific climate increased total utility between 3.4% and 9.2%.

**Table 4.** Opportunity cost of not adapting management plans to climate change showing the results for all criteria included in the utility function. The optimised plan under current climate is applied to climate change scenarios (ECHAM4, HadCM2) and compared with plans specifically optimised for the respective climate scenario (optEcham, optHad). NPV = Net Present Value including the discounted stumpage value in year 100,  $p=0.02$  [€ ha<sup>-1</sup>], MAI = mean annual timber increment [m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>], CS-F = mean carbon storage in the forest (above- and below-ground biomass of trees and carbon in the soil) [Mg ha<sup>-1</sup>], C-WP = mean carbon storage in wood products [Mg ha<sup>-1</sup>], fDW = average annual fresh deadwood [m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>], TH<sub>flow</sub> = coefficient of variation of decadal timber harvests [%], TH<sub>min</sub> = minimum harvested timber per decade [m<sup>3</sup> ha<sup>-1</sup>], U(sl) = aggregated stand level utility, U(ul) = aggregated unit level utility, maxTP= timber production scenario, maxCS = carbon sequestration scenario, MO = multi-objective scenario (including timber production, carbon sequestration and biodiversity). The plans with the highest total utility for each of the objective/climate scenario combinations are presented.

Criteria	Climate scenario				
	Current	OptEcham	ECHAM4	OptHad	HadCM2
<b>MaxTP objective scenario</b>					
NPV (€ ha <sup>-1</sup> )	7851	<b>8983</b>	9121	<b>8896</b>	8948
MAI (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	6.3	<b>7.9</b>	7.8	<b>7.6</b>	7.5
CS-F (Mg ha <sup>-1</sup> )	113.4	<b>122.4</b>	114.1	<b>121.2</b>	114.5
CS-WP (Mg ha <sup>-1</sup> )	10.3	<b>11.2</b>	12.0	<b>11.3</b>	11.7
fDW (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	0.4	<b>1.0</b>	0.6	<b>0.8</b>	0.5
TH <sub>flow</sub> (%)	29.7	<b>24.4</b>	36.2	<b>24.1</b>	38.2
TH <sub>min</sub> (m <sup>3</sup> ha <sup>-1</sup> )	46.6	<b>47.4</b>	46.7	<b>47.1</b>	45.8
U(sl)	0.4107	<b>0.5139</b>	0.5119	<b>0.4993</b>	0.4955
U(ul)	0.6930	<b>0.7292</b>	0.6551	<b>0.7288</b>	0.6381
Utotal	0.4954	<b>0.5785</b>	0.5549	<b>0.5682</b>	0.5383
<b>MaxCS objective scenario</b>					
NPV (€ ha <sup>-1</sup> )	7275	<b>8418</b>	8422	<b>8297</b>	8279
MAI (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	6.1	<b>7.6</b>	7.6	<b>7.4</b>	7.4
CS-F (Mg ha <sup>-1</sup> )	133.7	<b>139</b>	138.1	<b>140.6</b>	138.8
CS-WP (Mg ha <sup>-1</sup> )	9.2	<b>10.4</b>	10.6	<b>10.2</b>	10.4
fDW (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	1.6	<b>2.2</b>	2.1	<b>2.1</b>	2.0
TH <sub>flow</sub> (%)	57.2	<b>58.6</b>	59.0	<b>58.5</b>	57.3
TH <sub>min</sub> (m <sup>3</sup> ha <sup>-1</sup> )	37.7	<b>43.5</b>	38.8	<b>43.2</b>	36.5
U(sl)	0.4939	<b>0.5290</b>	0.5283	<b>0.5336</b>	0.5291
U(ul)	0.4520	<b>0.5217</b>	0.4653	<b>0.5189</b>	0.4381
Utotal	0.4814	<b>0.5268</b>	0.5094	<b>0.5292</b>	0.5018
<b>MO objective scenario</b>					
NPV (€ ha <sup>-1</sup> )	7047	<b>8292</b>	8116	<b>8106</b>	7987
MAI (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	5.9	<b>7.5</b>	7.4	<b>7.2</b>	7.1
CS-F (Mg ha <sup>-1</sup> )	133.5	<b>139.4</b>	139.1	<b>141.0</b>	139.6
CS-WP (Mg ha <sup>-1</sup> )	8.7	<b>9.9</b>	9.7	<b>9.8</b>	9.5
fDW (m <sup>3</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	1.8	<b>2.3</b>	2.5	<b>2.3</b>	2.4
TH <sub>flow</sub> (%)	33.1	<b>28.2</b>	39.9	<b>28.9</b>	43.8
TH <sub>min</sub> (m <sup>3</sup> ha <sup>-1</sup> )	33.6	<b>38.3</b>	32.1	<b>35.9</b>	26.3
U(sl)	0.5497	<b>0.6165</b>	0.6119	<b>0.6175</b>	0.6040
U(ul)	0.5949	<b>0.6521</b>	0.5459	<b>0.6332</b>	0.4883
Utotal	0.5633	<b>0.6272</b>	0.5921	<b>0.6222</b>	0.5693

\* Bold figures means that the numbers correspond to the plan specifically optimised for the respective climate.

## 4 DISCUSSION AND CONCLUSIONS

### 4.1 Evaluation of approach selected for the study

Forests provide different services beyond timber production, such as maintaining biodiversity, watershed and soil protection as well as recreation. An additional service provided by forests is what Jarvis et al. (2005) called “carbon forestry”, which emphasises the direct role of forest management in maintaining forest carbon stocks and enhancing forest sink capacity for carbon. The carbon discount in forest management has increased recently by the acknowledgement of the role of forests in the global carbon cycle through the adoption of the Kyoto Protocol. Moreover, it is known that management activities have several direct and indirect influences on the productivity of forest ecosystems and their C sequestration potential (Karjalainen 1996a,b, Nabuurs and Schelhaas 2002).

In this work, a process-based model was used to study how management, forest structure (in terms of age class distribution) and changing climatic conditions affect the growth, timber yield and carbon stocks in a boreal forest ecosystem, and investigate the implications for carbon stocks in harvested timber. The work was based on inventory data for an FMU (1451 ha) located in central Finland. In addition, a process-based growth model, a wood products model and an optimisation heuristic model were applied in combination in order to identify optimised management plans under multiple objectives (timber production, carbon sequestration and biodiversity in terms of deadwood). The study also evaluated the importance of adapting the forest planning to climate change.

The impacts of transient climate change scenarios on currently existing forests have only been addressed so far to a very limited extent and usually based on a business-as-usual management (e.g. Lasch et al. 1999, Lindner 2000, Lexer et al. 2002). For the work presented here, different stand treatment programmes (STP) were applied. These, differed from each other in the sense that mean stocking in the tree populations over the rotation was increased or decreased compared to the business-as-usual management. This allowed the identification of how sensitive growth, timber yield and carbon stocks are to the management. In this work the management recommendations applied until recently in practical Finnish forestry (Yrjölä 2002) were used to define the Basic Thinning regime BT(0,0). Even though the management recommendations have been slightly modified (making possible earlier thinning and final cutting) recently (Hyvän metsänhoidon ... 2006), they apply the same principles as the previous ones used in this work. Thus, the findings of this work should still be valid.

In addition, three different climate scenarios (current climate and two climate change scenarios) were applied to study the sensitivity of findings to climate change. As the STPs are adaptive per se to the effects of climate change on growth rate, a longer time than a normal planning period is required to get a clear climate change signal on shares of allocated STPs. This means that a long planning period (100 years) should be used, which in turn calls for robust and reliable models to project the likely consequences of a plan.

A novel feature of this study was the application of a detailed process-based growth model to project forest ecosystem development under a set of different management options to an FMU level planning problem. This made it possible to evaluate the effects of climate change on the planning solutions. Previously presented analyses have also shown that the process-based model used in this study is capable of simulating the growth and

development of tree stands under the current climate in a similar way than conventional growth and yield models (see Matala et al. 2003, Briceño-Elizondo et al. 2006). Since the predictions based on the process-based model are considered valid for the current climate and provided that the growth dynamics will be similar under the changing climate, the model predictions are expected to be realistic and plausible for the conditions of climate change because they are based on underlying physiological processes.

Several review articles propose approaches to structure and classify the large number of multicriteria analyses methods assisting in the informed choice of a method for a particular decision making problem (e.g. Hwang and Yoon 1981, Guitouni and Martel 1998). Most methods fall within three operational approaches (Roy 1985): (i) single-criterion synthesis approach; (ii) outranking synthesis approach; and (iii) interactive local judgement with trial and error iterations. In this work a method belonging to the first approach, assuming the existence of a utility function, was applied. A utility model was employed to combine all objective variables and constraints in an overall utility index which was then maximised by a heuristic optimisation method. In this approach, the management objectives were specified at the stand level and all stand treatment options were evaluated by means of criterion-specific preference functions. This approach required additional criteria at the unit level to satisfy constraints such as liquidity demand or spatial considerations (i.e. habitat requirements). These unit level constraints usually make the objective function non-additive which in turn favours heuristics instead of mathematical programming techniques. One advantage of the approach used was that interpretation of the model coefficients as relative weights of objectives and criteria was intuitively possible. This also makes the approach potentially suitable for multi-stakeholder planning situations in public participation (Kangas and Hytönen 2001, Munda 2004).

Some heuristics commonly used in forest planning problems include simulated annealing, tabu search, random ascent and genetic algorithms (Reeves 1993, Borges et al. 2002). In this study, an optimisation heuristic was used. The heuristic is similar to the HERO method as presented by Pukkala and Kangas (1993). This approach potentially carries the risk of getting trapped in a local optimum. However, Pukkala and Kurttila (2005) found that simple techniques such as HERO and random ascent are suitable approaches especially when spatial objectives are not included in the problem. The FMU used in this study consisted of 1018 stands, each having six alternative treatment programmes. Thus, the total number of possible different plans was  $6^{1018}$ . This clearly shows that it is not practical to compare and evaluate all available alternatives. Instead one relies on efficient numerical tools to search the decision space for feasible solutions.

Although the good practice guidance for land use, land-use change and forestry (GPG-LULUCF, IPCC 2003) proposes a coherent accounting scheme for the first commitment period (CP1) of the Kyoto Protocol, future accounting rules may differ significantly (Kurz et al. 2002, Kirschbaum and Cowie 2004). Because the time frame of the current study (100 years) extends far beyond the CP1, formal aspects of C accounting under the current Kyoto rules and regulations were not addressed. Instead, one general C accounting approach proposed in the literature was employed (see Richards and Stokes 1995, Newell and Stavins 2000). As there is not general convention on which method to apply for such large time horizons the mean storage approach was used where the C stocks were calculated as an average stock over the planning period assuming a null discount rate. From the perspective of the FMU, the price of C is zero, as projects within annex I countries are not eligible within the frame of clean development mechanism instruments (CDM) and by the absence of subsidies which compensate a forest owner for C sequestration by forest management.

## 4.2 Evaluation of the main findings

The results showed that an increase in temperature and precipitation with a concurrent elevation in CO<sub>2</sub> may enhance the average annual growth in central Finland by an average of 22 and 26% for HadCM2 and ECHAM4 climates, respectively. Previously Talkkari (1996, 1998) and Talkkari and Hypén (1996) found an increase of 10% in growth over the whole of Finland when management was based on the current recommendations. However, they excluded the direct effect of CO<sub>2</sub> on the growth in their computations. Under the climate change scenarios applied in this study, the total timber yield, and consequently C stock in harvested timber, increased by an average of 12% for HadCM2 and 13% for ECHAM4 over next 100 years in response to the increase in the total growth of stem wood.

Total C stock in the forest ecosystem in boreal conditions was increased on average by 6% for unthinned regime UT(0,0) under both climate change scenarios. For thinned regimes, the mean increment for the HadCM2 climate was 1%, while for the ECHAM4 climate the amount of C stock in the ecosystem decreased slightly depending on the thinning regime applied. A similar pattern in the total C stock was described by Karjalainen et al. (1999), who concluded that a moderate increase in temperature seems to enhance the C sequestration in forests, while a more pronounced temperature increase could make forests turn from C sinks into C sources.

Under climate change and regardless of the thinning regime, the C stock in trees increased also by an average of 6% and 8% for HadCM2 and ECHAM4, respectively. This is in concordance with previous results (Mäkipää et al. 1999, Karjalainen et al. 2003). In contrast, C stock in soil decreased compared to current climate conditions; the relative decrease was smaller for unthinned regime UT(0,0) due to the higher mortality compared to thinned ones with resulting supply of C to the soil. The decrease of C stock in soil has also been described by other authors, who found that climate change will likely increase microbial decomposition of soil organic matter, causing an increased transfer of C from soil to the atmosphere, hence reducing the sink (Grace 2001, Karjalainen et al. 2003). However, other authors have suggested that C stock in soil may not always decrease in response to warming (Thornley and Cannell 2001). In this work, greater increases of C stock in trees and C stock in harvested timber was observed for the ECHAM4 climate compared to the HadCM2 climate. This was due to the higher temperature and precipitation increment applied in the ECHAM4 climate scenario. On the other hand, the higher temperatures increased the decomposition of C present in soil.

Management had a clear effect on the timber yield and the mean C stock in the forest ecosystem. In general, any increase in tree stocking over the rotation increased the timber yield and the C stock in the forest ecosystem compared to levels of the business-as-usual thinning regime (BT(0,0)). The highest C stock (Paper II) and the highest timber yield (Paper I) in the forest ecosystem were found when basal area triggering the thinning (upper limit) and the remaining stock after thinning were increased by 30% (BT(30,30)). This result is in concordance with the findings of Thornley and Cannell (2000), who conclude that in a forest ecosystem it is possible to increase the timber yield and the C storage at the same time. There is, thus, a clear need to adapt management in order to enhance carbon sequestration in-situ and also concurrently to enhance timber production. The preference of higher stand stocking over the rotation was also supported by the economic assessment of thinning regimes as indicated by the increased net present value (NPV). This result is, however, sensitive to the discount rate used in calculating the values of NPV. Regardless of the climate scenario, the C stock in the forest ecosystem was highest in the unthinned

regime (UT(0,0)) whereas the NPV was smallest. This result indicated that in commercial terms the unthinned regime (with only final cutting) is not a real option.

There was a large difference of increment in C stock in forest ecosystem for thinning regime BT(30,30) and unthinned regime UT(0,0) compared to the Basic Thinning regime BT(0,0); i.e. increments being 11% and 45%, respectively. This suggests that in order to enhance C stock without a rise in the mortality in the stands the thinning thresholds may be increased further than the 30% used in this study. However, the C stock in forest ecosystem also depends on the forest structure (tree species and age class distribution) and properties of the site (Mäkipää et al. 1998, 1999, Vucetich et al. 2000, Pussinen et al. 2002). In this study, it was shown that the normal and equal age class distributions produced fairly balanced timber harvests over time. The initial age class distribution representing mainly sapling stands (left-skewed distribution) concentrated cuttings on the latter years of the simulation period. On the other hand, if the initial age class distribution representing mainly old stands was used (right-skewed distribution), the cuttings were concentrated on the early years of the rotation. In the latter case, the NPV of the timber harvest (with discount rates 1, 3 and 5%) was the highest, because the value of the timber from cuttings in the early years of the simulation was less negatively affected by the discount rates than in other cases with late cuttings.

Moreover, the simulations showed that the initial age class distribution had some influence on the estimations of timber yield increase (%) when comparing results under the current climate and under the changing climate; the highest increase for managed forests was found for the normal distribution and the smallest for the left-skewed distribution. Based on these findings, it is still hard to suggest a preferable initial age class distribution because the age class distribution changes over time as a result of forest dynamics and management applied. However, it is useful to know the differences in the predictions of the forest productivity at a landscape level considering different initial age class distributions. This is especially the case when taking an existing FMU and trying to predict its development under changing climatic conditions or under different management regimes. As demonstrated here, the results cannot be directly generalised to other areas without taking into account the structure of the analysed forest (age class and species distribution) at the beginning of the simulation. The initial age class distribution had, however, no large impact on the average C stock in the forest ecosystem over 100 years; i.e. the maximum difference was 3% between the lowest average C stock in ecosystem (left-skewed distribution) and the highest average stock (right-skewed distribution, representing mainly old stands). This was not the case for management, which had a clear effect on the mean C stock in the forest ecosystem, regardless of the initial age class distribution applied.

In this study, the cost of C sequestration by sink enhancement was calculated excluding the C stock in wood-based products from the calculations. This accounts for a smaller C stock than in reality, and thus, the cost of C would be lower than calculated here. There are significant variations between studies regarding the magnitude and costs of C sequestration (Kolshus 2001); i.e. previous studies show that estimates of the cost of forest C sequestration range from 1 to 100 € Mg<sup>-1</sup> (Sedjo et al. 1995, Stavins 1999, IPCC 2001). In this study, depending on the initial age class distribution and the discount rate used in the simulations, the potential cost of C sequestration ranged from 21 to 52 € Mg<sup>-1</sup> when shifting the management from BT(30,30), maximising timber, to UT(0,0), maximising C stocks. However, it is possible to increase C stocks in the forest ecosystem without any loss in NPV compared to BT(0,0).

This study demonstrates the importance of analysing changes in the thinning thresholds, where there are no empirical data to inform decision makers. Simulations also showed the importance of taking into account the initial age class distribution of the forest ecosystem when trying to predict its future development. This kind of results can serve as a guide to forest managers and other decision makers. In addition, they might be important for policy makers who might seek to concurrently enhance carbon sequestration and timber production. The implications of these new thresholds will not lead to losses in monetary terms and could help to enhance C sinks.

To consider the benefits of C storage in wood products, a wood products model was also applied in this study. The model used was an adaptation and extension of previous examples (Karjalainen et al. 1994, Eggers 2002). Including the C storage in the wood products pool allowed for a more realistic and comprehensive evaluation of benefits produced by a particular forest management plan within multiple purpose forestry (Briceño-Elizondo and Lexer 2004). In the presented study, the characterisation of forest biodiversity was confined to the amount of annual fresh deadwood, which is considered a key attribute of forest biodiversity (Samuelsson et al. 1994, Schuck et al. 2004). Additionally, in the stand treatment options no species change was considered although species choice affects timber production and carbon stocks in the forest ecosystem (Papers I-II). However, in further studies spatial habitat indices could also be included as a decision criterion (see Naesset 1997).

Why is there a need for an optimisation at the FMU level? Why not use an optimal STP at the stand level for the entire FMU? As shown in this work, no solution generated by applying one STP for the entire FMU seems acceptable in practice even if that STP maximised one of the criteria. For instance, choosing one STP for the entire unit just because it maximised the NPV implied very uneven harvest schedules and low carbon sequestration. The STP that maximised carbon sequestration yielded a very low net present value, a very uneven flow of timber harvests and an extremely low minimum harvested timber volume per decade.

As expected, significant differences between the optimised management plans for the different objective scenarios were found. In addition, significant differences were also found between optimised plans for the different climate scenarios, indicating that climate does affect optimal planning solutions. Moreover, in order to find the cost of not adapting the management plans to climate change an analysis was made of how a management plan specifically optimised under current climate performs under climate change conditions. To respond to that issue, the optimal plan for current climate was applied under the two different climate change scenarios (ECHAM4 and HadCM2) and results compared with optimal plans for ECHAM4 and HadCM2 climate scenarios. In this example, the gain in total utility through optimising a management plan specifically to changing climatic conditions was between +3.4% and +9.2%, depending on the objective and the climate scenario. Comparing these results with the increase in total utility of plans optimised for the current and climate change conditions reveals that optimisation was responsible for approximately 30% to 50% of these gains, the rest comes from increased production due to climate change.

It is recommended to include possible future climate change assumptions in forest planning. In addition, based on the findings of this work, the combined use of process-based growth modelling and multi-objective optimisation heuristic seems to provide an efficient tool to support forest planning and decision-making in identification of optimised management plans under multiple objectives and climate change conditions.



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