Dissertationes Forestales 24

Stand level analysis on the effects of management and climate change on the growth and timber yield with implications on carbon stocks in boreal forest ecosystem: a model based approach

Elemer Briceño-Elizondo
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Academic Dissertation

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ABSTRACT

The main aim of this study was to investigate based on process-based ecosystem model simulations how management and climate change affect the growth, timber yield and carbon stocks in boreal forest ecosystem (Papers I-II). In addition, it was studied how the management affects under varying climate the possibility to meet multi-purpose demands in regard to timber production, carbon sequestration and biodiversity (in terms of dead wood) based on a stochastic multi-criteria analysis (Paper IV). Simulations were carried out in Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst. L.) and silver birch (*Betula pendula*) stands growing in the southern and northern Finland. In addition to current climate, two different climate change scenarios and eight different stand treatment programmes (i.e. one unthinned and seven thinning regimes) were applied in simulations over 100 years. The stand treatment programmes differed from each other in the sense that the mean stocking varied in the stand over the rotation. The simulation results were also used as data for a multi-criteria analysis, in which expected utility was calculated with an additive utility model (Paper IV). In this context, it was also utilized a wood products model developed (Paper III), to estimate carbon stocks in wood products.

The model based analyses indicated that in unthinned stands, the growth and carbon stock was on an average always higher compared to thinned stands regardless of tree species, sites and climate scenarios compared (Papers I-II). However, in regard to thinning regimes, the one in which the mean stocking was kept an average higher over a rotation compared to the current thinning guidelines, had also a higher growth and timber yield (Paper I). This increased also the mean carbon stock both in the forest ecosystem and in the harvested timber compared to the current thinning guidelines (Paper II). The climate change (regardless of scenarios) in itself enhanced growth, timber yield and carbon stocks in relative terms more in the north than in the south regardless of tree species.

The utility was also maximized, regardless of site, tree species and climate scenario applied, by leaving the stand unthinned over a rotation or alternatively by keeping the stocking level higher (e.g. 30% higher) over the simulation compared to the current thinning guidelines (Paper IV). When accurate weights for criteria of timber production, carbon sequestration and dead wood were used to reduce uncertainty, expected utility did not change noticeably. As a conclusion, the selection of stand treatment programme was found to have an important role, regardless of tree species, sites and climate scenarios, on the timber production, but also on other benefits such as carbon sequestration and amount of dead wood in the forest ecosystem.

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This work was mainly funded through the Finnish Centre of Excellence Programme (2000-2005), under the Centre of Excellence for Forest Ecology and Management (Project no. 64308), co-ordinated by Academy Prof. Seppo Kellomäki, University of Joensuu, Faculty of Forestry. It was also partly funded by the Graduate School of Forest Sciences, University of Joensuu and by the SilviStrat-project "Silvicultural Response Strategies to Climatic Change in Management of European Forests" (Project no. EVK2-2000-00723) funded by the European Union. The support provided by the Academy of Finland, the National Technology Agency (Tekes), the European Union and the University of Joensuu is acknowledged.

I would like to extend my special thanks to my supervisors, Academy Prof. Seppo Kellomäki and Prof. Heli Peltola from the University of Joensuu and Prof. Manfred Lexer from the University of Natural Resources and Applied Life Sciences, Vienna for their excellent guidance. Mr. Hannu Väisänen is deeply thanked as well for his contribution concerning the simulations performed for my work. Colleagues Mr. Dietmar Jäger and Mr. Jordi Garcia-Gonzalo are also kindly acknowledged for their contributions on the papers. Mr. David Gritten is thanked for helping in revising the language of this thesis. I would like to thank also other colleagues from the Faculty of Forestry, University of Joensuu for their support as well as the partners of the SilviStrat project for their fruitful comments.

Finally, I would like to dedicate this PhD thesis especially to my father and mother, Dr. Elemer Briceño-Salazar and Mrs. Mireya Elizondo-Jimenez; without their love and support I could have not gone so far in my life. I also would like to dedicate this thesis to my brothers and sisters and our next generation due to their love and support beyond borders. Last but not the least I would like to extend my gratitude to my motherland Costa Rica for teaching me to understand the value of work and peace.

LIST OF ORIGINAL ARTICLES

I. Briceño-Elizondo, E.; Garcia-Gonzalo, J.; Peltola, H.; Matala, J. and Kellomäki, S. 2006. Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions. *Submitted manuscript.*

II. Briceño-Elizondo, E.; Garcia-Gonzalo, J.; Peltola, H.; Kellomäki, S. 2006. Carbon stocks in the boreal forest ecosystem in current and changing climatic conditions under different management regimes. Environmental Science and Policy 9(3): 237-252.

III. Briceño-Elizondo, E.; Lexer, M.J. 2004. Estimating carbon sequestration in the wood products pool: Model adaptation and application to Austrian conditions. Centralblatt für das gesamte Forstwesen (Austrian Journal of Forest Sceince) 121 (2): 99-119.

IV. Briceño-Elizondo, E.; Jäger D.; Lexer, M.; Garcia-Gonzalo, J.; Peltola, H.; Kellomäki, S. 2006. Multi-criteria evaluation of multi-purpose stand treatment programmes for Finnish boreal forests under changing climate. *Submitted manuscript.*

Elemer Briceño-Elizondo had main responsibility in regard to all the work done in Papers I-IV. But Mr Dietmar Jäger and Prof. Manfred Lexer have carried out the actual multi-criteria simulations in Paper IV and the co-authors of separate papers (I-IV) have commented the manuscripts.

CONTENTS

1. INTRODUCTION

1.1 Background

Presently forest planning solely for timber production is no longer sufficient and forest planning and forest decision making are facing new requirements (Laukkanen et al. 2002). As efforts towards this, the role of forests in the global carbon cycle and their potential contribution in mitigating human-induced climate change was underlined by the Kyoto-Protocol (UNFCCC 1997 [Arts.3.3 and 3.4], Karjalainen et al. 2000, Liski et al. 2000). However, only few studies are available about the opportunities provided by managed forests for carbon sequestration and the adaptive response strategies (Karjalainen, 1996; Müller 1997). The measures suggested previously to enhance the carbon sequestration along with timber production have included following options, for example: lengthening of the rotation (Kaipainen et al. 2004, Liski et al 2001), shifting from clear-cutting systems to selective harvesting (Read *et al.* 2001), increasing the percentage of protected forests (Read et al. 2001) and improved silvicultural techniques, including fertilisation (Mäkipää et al. 1998a, Olsson et al. 2005). In addition, thinning practices (e.g. timing, intensity and interval) are also of primary importance in controlling the stand stocking and carbon stock in forest ecosystem, and the carbon fixation rate into the forest ecosystem (Thornley and Cannell, 2000, Karjalainen 1996). Obviously, the possible adaptation of management to climate change is affected by the sensitivity of the forest growth and dynamics to the changes expected to occur in the climatic and edaphic properties of the forest sites (Lindner 2000, Lasch et al. 2002, Spittlehouse and Stewart 2003, Lasch et al. 2005).

In Finland, which is situated in the boreal forest region, growth is currently limited by low summer temperatures. However, during the next 100 years, the climate is forecasted to be 2–7˚C warmer than currently (Carter et al. 2002). Higher temperatures and concurrent elevation in atmospheric CO_2, as well as increased availability of nitrogen, on average may increase growth in forests, though on sandy soils the availability of water may limit that growth (Freeman et al. 2005). This may affect the silvicultural response of the forest ecosystem. Therefore, there exists a clear need to better understand the future management options when aiming at utilizing the increasing potentials for timber production but still maintaining a high capacity of the forest to sequestrate carbon. The expected increase in the forest growth under changing climate may, for example, imply that the length of the rotation could be reduced if the maturity criteria for regeneration remain the same as under the current climate (Kellomäki et al. 1997).

To aid in the decision and planning process, forest managers can use a number of tools which assist them in prediction of growth from different forest types. On one hand, there are available traditional statistical growth and yield models, such as Motti (Hynynen et al. 2002, Matala et al. 2003), which has been integrated into the MELA planning system for Finnish conditions. For similar conditions, there has been developed in recent years process-based models, such as the FinnFor model (Strandman et al, 1993, Kellomäki et al 1997), which is used in this study. Statistical models are usually preferred in locally focused predictions (Matala et al. 2005). However, these models are based on the assumption that the prevailing climate will continue unchanged and therefore, process-based models are widely used in projections of the impacts of climate change on forests, although they are typically complex by structure with many parameters (Matala et al. 2003).

There have also been developed approaches to properly account for the consequences of land use on the wood products carbon pool. At the national level, for example, in the context of the International Panel for Climate Change (IPCC) guidelines of the United Nations, Brown et al. (1998) presented three different approaches to explicitly account for carbon stocks in wood products: (i) the atmospheric flow approach, (ii) the stock change approach, and (iii) the production approach which essentially is a stock change approach with the exclusion of trade. While these approaches are important for calculating national carbon balances, they cannot be directly used to evaluate the effect of forest management on carbon sequestration at lower aggregation levels, where management decisions are actually made. So far, there exist only few attempts to investigate the faith of harvest levels and wood products pool and/or fossil fuel substitution in order to obtain a more integrated view on management consequences (Schlamadinger et al. 1996, Karjalainen et al. 2002, Karjalainen et al. 2003). For this purpose, as an example, the EFISCEN model has been used in a regional model, to link consumption rates and wood products trade flows (Nabuurs et al. 2000). Moreover, the CO2FIX model in its current version is capable to calculate annual carbon stocks including the wood products chain at the stand level (Nabuurs et al. 2002).

In the future, multi-resource nature of modern forestry will demand managers to assess the potential impacts of decisions on a broad range of forest attributes, e.g. related to biodiversity, timber production, carbon sequestration, recreation and other values (Seely et al. 2004). This may create conflicts in terms of what is preferred from forest management. The integration problem for the multiple forest uses can, however, be compensated with methodologies of multi-objective decision support (Kangas et al. 2000), in which the different objectives can be taken into account in a sound and transparent manner to select the most desirable alternative, according to a set of preferences (Kangas and Kangas 2005, Aouni et al. 2005). In general, forest planning consists of producing decision alternatives (i.e., stand treatment programmes) to choose from, predicting and evaluating their consequences and ranking the alternatives in a systematic way. Even with the help of these techniques, forest planning is always made under conditions of risk or uncertainty, due to the long production periods and exogenous factors which are beyond the control of the decision maker. For instance, reasons for uncertainty might be measurement or prediction error in the decision variables. Other sources of uncertainty can come from exogenous influences, such as those related to the inability to identify the preferences of stakeholders and decision makers; but also from limited knowledge concerning the effect of the future climate, as mentioned earlier. It is difficult in a unilateral decision making situation to accurately capture the preference structure of a decision maker. Such difficulty in characterizing preferences accurately increases substantially in multi-lateral decision making situations and in public participation (Van. Den. Honert, 1998). The extraction of preferences as a prerequisite to the rational evaluation of decision alternatives is a major internal source of uncertainty (Paulson and Zahir, 1995), which is necessary to consider in planning. Numerous forest planning applications have been presented employing multiple criteria decision making methods to compare or discern from decision alternatives with respect to decision criteria (Romero 1996, Kangas et al. 2000, Pykäläinen et al. 2001, Store and Kangas 2001, Vacik and Lexer 2001, Ananda and Herath 2003, Pukkala et al. 2003).

1.2. Aims of this study

The main aim of this study was to investigate based on process-based model simulations how management and climate change affect the growth, timber yield and carbon stocks in boreal forest ecosystem. In addition, it was also studied how the management affects under varying climate the possibility to meet multi-purpose demands in regard to timber production, carbon sequestration and biodiversity (in terms of dead wood) based on a stochastic multi-criteria analysis. More specifically, this study had following separate research tasks:

i. To investigate the sensitivity of growth and timber yield to management and climate change in Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst. L.) and silver birch (*Betula pendula*) stands growing in the southern and northern Finland (Paper I). In this context the model output is analyzed against sensitivity to climatic and site factors and thinning intensity; moreover climate change scenarios and varying thinning regimes are used to predict consequences to growth and timber yield.

ii. To investigate the sensitivity of carbon stocks in the forest ecosystem (in soil, above and below ground tree biomass) and in the harvested timber to management and climate change in Scots pine, Norway spruce and silver birch stands growing in the southern and northern Finland (Paper II).

iii. To investigate how the management affects under varying climate the possibility to meet multi-purpose demands in regard to timber production, carbon sequestration and biodiversity (in terms of dead wood) in Scots pine, Norway spruce and silver birch stands growing in the southern and northern Finland; based on a stochastic multi-criteria analysis (Paper IV). In this context, it is utilized also the Wood Products Model originally developed and applied for Austrian conditions (Paper III), but structured and parameterized for Finnish conditions for this study.

2. MATERIAL AND METHODS

2.1 General outlines

A process-based ecosystem model FinnFor (Strandman et al. 1993, Kellomäki and Väisänen 1997, Kellomäki et al. 1997) is used in this study to simulate the growth and dynamics of boreal forest stands growing in Finnish conditions. More in details, the simulations are carried out in Scots pine, Norway spruce and silver birch stands growing in the southern and northern Finland. In addition to current climate, two different climate change scenarios (named ECHAM4 and HadCM2, see details in chapter 2.4) and number of different stand treatment programmes with varying levels of stocking over rotation are applied in the simulations. In this context, a sensitivity analysis of the FinnFor model output to environmental conditions (e.g. temperature, atmospheric CO_2, precipitation, nitrogen availability) and thinning intensity, regardless of tree species, will also be carried out.

The simulation outputs to be analysed under varying management and climate scenarios, and regardless of tree species and sites, include: stem volume growth, timber yield (and its percentage of logs), amount of dead wood (of trees) and carbon stocks in boreal forest ecosystem (in soil, above and below ground tree biomass) and carbon stock in harvested timber. In this context, harvested timber (pulp, logs) will also be used as input to the wood products model developed to estimate carbon stocks in wood products. In this model (WPM-IS), most of the state variables distribute the matter further in the system according to specified distribution coefficients for the manufacturing industry.

The estimated average carbon stocks in wood products are then used further in multi-criteria analyses along with other results for stand level simulations over 100 years. This multi-criteria analysis follows principles of utility theory. It helps to analyse how, for example, the management affects under varying climate the possibility to meet multi-purpose demands in regard to timber production, carbon sequestration and biodiversity (in terms of dead wood); and makes it possible to analyse simultaneously also the uncertainty related to preferences of the decision maker. The outlines of the work presented above and its logic can be seen in Figure 1.

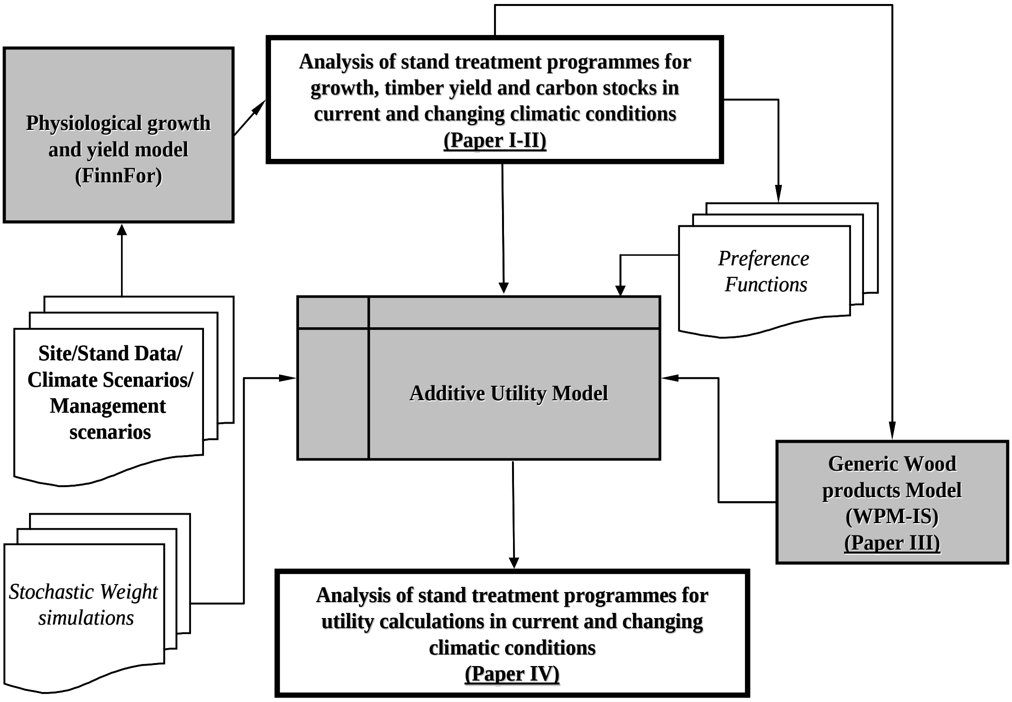

Figure 1. Outlines and models used in this work.

2.2 Description of the models used in the study

FinnFor

This study utilizes the FinnFor model originally developed by Kellomäki and Väisänen (1997) for assessing the effects of the climate change on the boreal forests (Figure 2). The dynamics of the boreal forest ecosystem are directly linked to the climate (e.g. temperature, atmospheric CO_2, precipitation, radiation) via photosynthesis, respiration and transpiration. Furthermore, hydrological (water availability) and nutrient (e.g. nitrogen availability) cycles indirectly couple the dynamics of the ecosystem to climate change through soil processes, which represent the thermal and hydraulic conditions in soil, and the decomposition of litter and humus with the mineralization of nitrogen. The model computations cover an entire year representing active and dormant seasons. These calculations are carried out on a cohort basis; i.e. the tree population is described by size cohorts specified by tree species, the number of trees in the cohort (trees per hectare), diameter (cm), height (m) and age (year).

Each cohort is represented by an object tree, whose physiological performance is modelled in terms of photosynthesis and respiration in order to obtain the amount of photosynthates available annually for growth of mass in the object tree, with the consequent development of the tree population over time. In the model, the thinning reduces foliage (LAI) of the tree population in linear correlation to the foliage mass in the removed trees. Recovery of LAI is, thus, a function of the thinning regime and net ecosystem productivity (i.e. net photosynthesis of trees) of the remaining trees. The dynamics of LAI control the transfer of radiation in the canopy and water to the soil. Furthermore, thinning disturbances increase litter in the soil in the form of logging residues, with a consequent increase of available nitrogen.

The inverse relationship between the stand density and the mean volume of stems was used to drive the mortality of trees, but this was supplemented by the survival of object trees (Hynynen 1993, Hynynen et al. 2002). At the beginning of each simulation step, the survival probability is calculated for each cohort based on (i) the within-stand competition model and (ii) the life-span of the trees. At the end of each simulation step, the total stocking of trees is checked in order to ensure that the stocking falls below the self-thinning line which determines the maximum allowable number of trees in a stand. Thereafter, the ratio between maximum tree number and predicted number is calculated. If this ratio is less than one, the predicted number in each cohort will be multiplied by the ratio to decrease the survival and increase the mortality, until the simulated number of trees equals to the maximum allowable number.

The model has been parameterised for Scots pine, Norway spruce and silver birch, and it includes a species-specific thinning procedure for stocking control. The validation and performance of the model has been presented and studied in detail in several papers regarding: (i) model validation against growth and yield tables (Kellomäki and Väisänen 1997), (ii) model validation against eddy covariance measurements (Kramer et al. 2002), and (iii) model validation against measurements of the growth history of trees in thinning experiments (Matala et al. 2003). Moreover, dynamics of hydrological and nitrogen cycles included in the model have been validated recently by Laurén et al. (2005) against the long-term monitoring data representing these processes in the scale of small watershed. Furthermore, a model intercomparison study employing FinnFor and a conventional growth and yield model has been also carried out recently (Matala et al. 2003). These analyses have shown that the physiological model used in this study is capable to simulate the growth and development of tree stands in a similar way than more conventional growth and yield models do. Also in this work (I) further analysis were preformed to test the validity of the model to changing climatic conditions, by simulating the growth response of the model against Motti model simulations along a latitudinal gradient for different sites in Finland (Figure 1, I) and effects of the FinnFor model to increasing temperature and changes in precipitation (Figure 3, I).

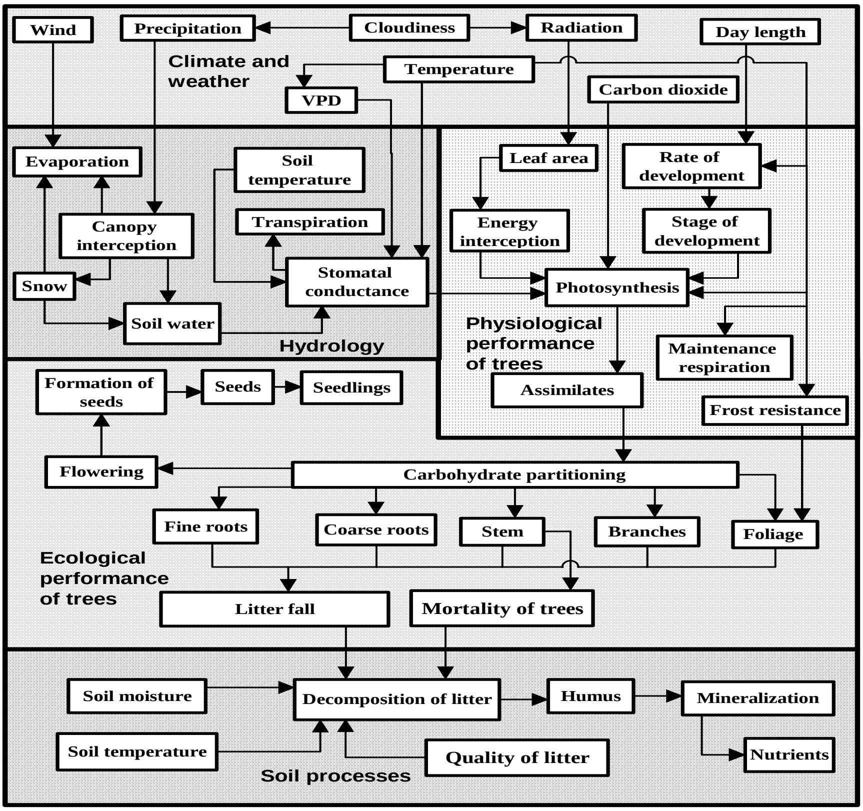

Figure 2. Some main structural and functional properties of the process-based (FinnFor) model used in simulations.

Wood products model WPM-IS

The wood products model developed related to this work (Paper III), simulates the temporary storage and recycling of carbon in wood products. The model keeps track of carbon in wood as processed in different production lines and operates on a yearly time interval (Table 1, III).

Most of the state variables distribute the matter further in the system according to specified distribution coefficients for the manufacturing industry. The sequence of calculations is initiated with the allocation of harvested timber into four production lines (Table 1, III). Carbon finally flows into commodities or use categories. After the end of product's lifecycle, carbon is put to recycling, landfill deposition or use as biofuel. Eventually, the carbon will be released into the atmosphere. In this study, the focus is put on the average storage in commodities, excluding the accumulation in landfills.

The structure of wood products model as applied in this study follows closely the conception and parameterization from Karjalainen et al. (1994) and Eggers (2002). The parameters for those studies have been estimated based on data from Finnish Yearbooks of Forest Statistics and on an extensive parameterization scheme for Europe based on FAOSTAT data bases (FAO, 2000; Eggers, 2002). The parameters and structure used for the Finnish conditions are presented in the Annex (Table 1, Figure 1). Assumptions on the production line efficiency and on the allocation of timber assortments to production lines were kept constant throughout the entire simulation period.

Additive utility model

The simulations based on FinnFor and WPM-IS models provide input data for the multi-criteria analysis of management alternatives. The stand treatment programmes (STPs) are evaluated here in regard to their potential to meet the demands of multi-objective forestry. This analysis is performed at the stand level to evaluate the competitiveness of STPs in terms of utility using the information generated in previous simulations. This will give an initial point of start to further studies trying to analyze the combination of given STPs at the unit level. The method used is an additive utility model, in which an overall utility index is calculated based on a set of management objectives, each broken down into a set of decision criteria. The utility of alternative (i) is described here by a linear additive model:

$$U_i = \sum_{j=1}^{n} w_j U_j\left(x_{ij}\right) \tag{1}$$

where U_i is the total expected utility from the sum of partial utilities $U_j(x_{ij})$, w_j is the relative weight (i.e., importance) of the partial objective (j) (j=1, …n), respectively. The weights have to be non-negative and sum up to 1. The weights of partial objectives and criteria were subjected to uncertainty due to missing exact stakeholder preference information. Probability distributions for individual weights were defined based on qualitative information. A Monte Carlo approach was employed to assign weights to partial objectives and criteria. The utility from partial objectives is calculated from linear preference functions which measure the performance of each alternative (i) with regard to (k) decision criteria:

$$U_j\left(x_{ij}\right) = \sum_{k=1}^{m} v_{jk} P_{ijk} \tag{2}$$

where P_{ikj} is the preference for the performance of alternative (i) with regard to criterion (k) and v_{jk} the relative weight (i.e., importance) of criterion (k) (k=1,2,...m) regarding the parent partial objective (j). The weights have to be non-negative and add up to 1. The preference functions permits the combination of decision criteria on different measurement units to a single, unitless scale.

From the utility model (Eqs. (1) and (2)) the expected utility of a stand treatment programme, under a given climate, can be calculated. However, given the uncertainty with regard to future climatic conditions it is useful to determine the overall expected utility as the composite of the utilities under all analysed climate scenarios (Eq. 3). The parameters c_l can be interpreted as subjective probabilities of the climate scenarios:

$$U_{total,i} = \sum_{l=1}^{p} c_l \cdot U_{i,l} \qquad (3)$$

$$\sum_{l=1}^{p} c_l = 1$$

where $U_{total,i}$ is the total expected utility of an alternative (i) under a given climate scenario (l), and c_l can be interpreted as subjective probability of occurrence of climate scenario (l). In the current analysis, timber production (TP), carbon sequestration (CS) and biodiversity (BD) are considered as partial objectives. These variables are selected due to the relevance they have been given in forestry in Finland and the role of carbon sequestration outlined by the Kyoto protocol. TP was further factorized into the decision criteria net present value (NPV) and mean annual increment, excluding deadwood (MAI). The partial objective CS was separated into mean carbon storage over the planning period in the forest ecosystem (CS-F) and mean storage in the wood products pool (CS-WP). Forest ecosystem carbon includes tree biomass above and belowground, and soil organic matter. BD is an objective which is particularly difficult to operationalize (e.g., Neumann et al. 2001, Pitkänen 1998, Puumalainen et al. 2003,). Here it was characterized by the average annual fresh deadwood of trees (Humphrey et al. 2002; Harper et al. 2005). Figure 3 shows the complete decision hierarchy for the study.

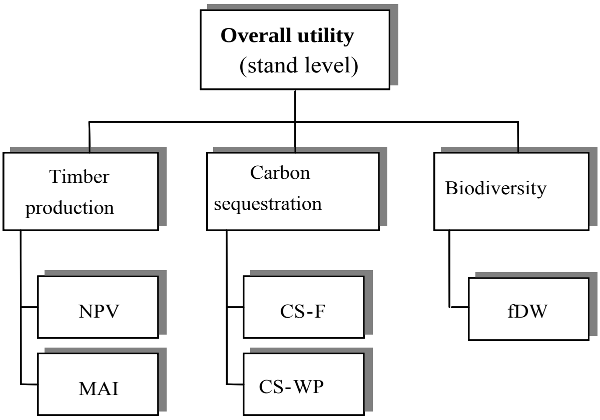

Figure 3. Decision hierarchy for the evaluation of stand treatment programmes. Legend: NPV = net present value, MAI = average production over simulation period with the exclusion of deadwood, CS-F = mean carbon storage in the forest, CS-WP = mean carbon storage in the wood products pool, fDW: average annual fresh deadwood.

2.3. Simulations with management, sites and climate scenarios applied in the studies (I, II, IV)

Outlines for simulations

The simulations are done for a site in southern boreal (Kuopio, 62°58'N 27°40'E) and for a site in northern boreal forests (Rovaniemi, 66°58'N 25°40'E) (Figure 4). Regardless of the site and tree species, the density of the initial stand was 2 500 seedlings per hectare. These were divided into five cohorts of 500 seedlings each. The initial height of the five seedling cohorts was 1.00, 1.15, 1.30, 1.45 and 1.60 m. Similarly, the initial diameter at the stem butt was 1.00, 1.15, 1.30, 1.45 and 1.60 cm, respectively. The simulations, described in detail below, are performed into two phases. First, the stands are run in preliminary simulations to test the response of the model to variation in climate parameters, CO_2, nitrogen content and thinning intensity. Second, the same initial stands are used for simulations, where a selection of management scenarios is further used to analyse growth, timber production and carbon stocks under current climate and two alternative climate change scenarios (Figure 5).

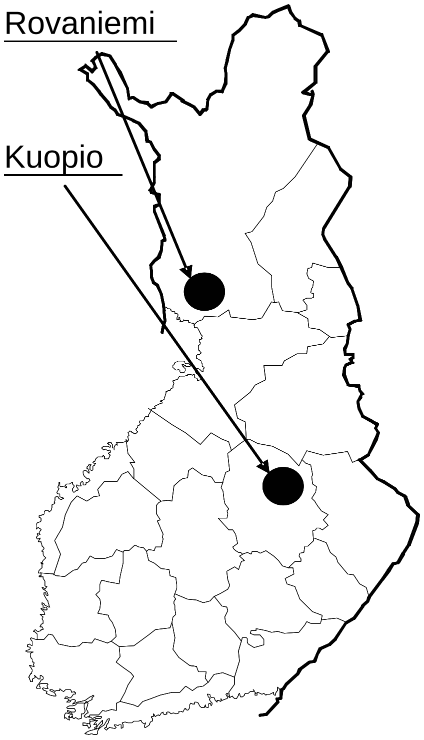

Figure 4. Location of sites simulated for the study.

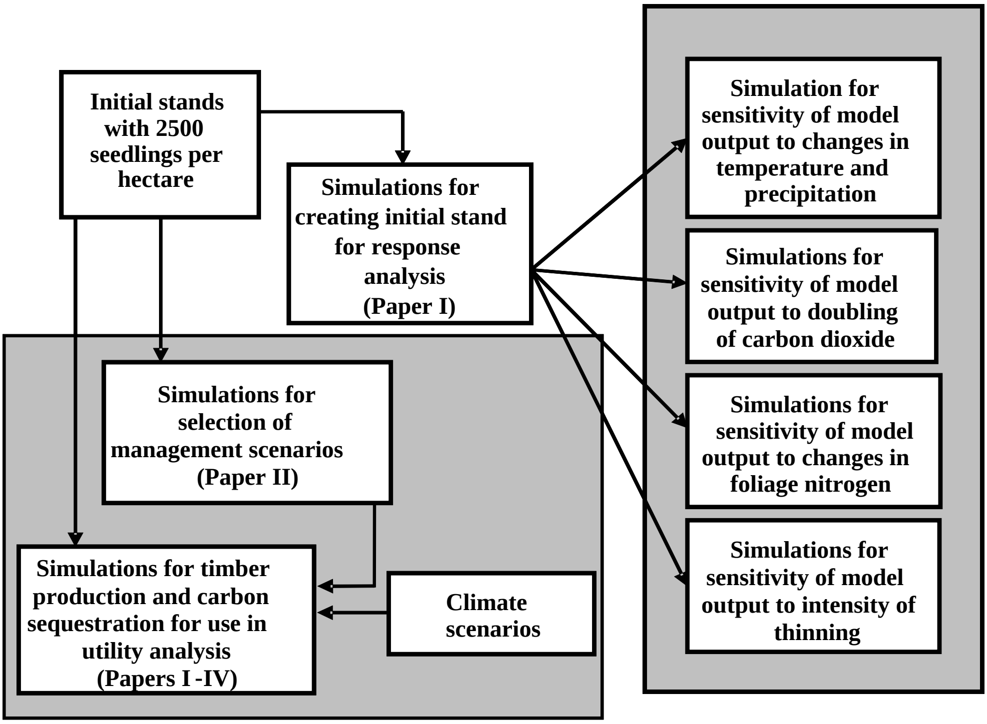

Figure 5. Schematic route of simulations done for analyses on the response of model output to climate change and management, and further simulations for analyses on the impacts of climate change and management on growth, timber production and carbon stocks.

Sensitivity analyses of FinnFor model predictions for growth and timber yield in regard to changes in climatic conditions, nitrogen availability and management

Preliminary simulations are performed to test the response of FinnFor output to the changes in climatic parameters (Paper I) with regard to growth. For this purpose, conditions representing the current climate are changed systematically. First, the daily mean temperature is increased up to +5.0 °C (using 1 °C steps). Secondly, the current precipitation is increased/decreased +/-10%, +/-20%; with a use of stable CO_2 concentration of 350 and 700 ppm. In this analysis, the current species-specific nitrogen content of foliage is also increased by 20 % (i.e. current and +20% values being 1.3% and 1.56% for Scots pine, 2.0% and 2.4% for Norway spruce and 2.5% and 3.0% for silver birch). Both sites were of the *Myrtillus* type in southern Finland and its equivalent in northern Finland, which is suitable for all three tree species (Scots pine, Norway spruce and silver birch). The soil in each case was a till with a high water retention capacity. No management were used in simulations representing the current climate (1961-1990) specific to the sites. Simulation period is 100 years, but the response was analyzed over 30 years starting 15 years prior to the culmination of growth and terminating 15 years after the culmination by applying the initial stands presented in Table 2, Paper I.

The response of the model performance to thinning is studied under current climate in term of the availability of resources and the consequent production of photosynthates and biomass per remaining trees (amount of precipitation, nitrogen availability, growth, mean net ecosystem productivity). The initial tree stands in simulations are the same as those used for the analysis of the climate sensitivity (Table 2, Paper I); where four different thinning regimes are applied; i.e. no thinning and the reduction in basal by 25% (light thinning), 35% (currently recommended thinning) and 42% (heavy thinning) regardless of tree species.

Sites and initial stand conditions for impact analyses

Further simulation runs in this work represent two sites in Finland, one for southern boreal forests, close to Kuopio (62°58'N 27°40'E), and one for northern boreal forests, close to Rovaniemi (66°58'N 25°40'E), being the same ones used previously. Regardless of the site and tree species, the density of the initial population was 2 500 five-year-old seedlings per hectare, growing a medium fertility site (*Myrtillus* type, which is suitable for all three tree species). These were divided into size cohorts in the same way as in the above response analysis.

Management scenarios

In constructing the stand treatment programmes for the analysis, the recommendations applied in practical forestry (Yrjölä 2002) were used to define the basic intensity of thinning (Basic Thinning) around which the intensity of thinning was varied. The recommended thinning guidelines, used in this study, are site and species-specific, and they employ the dominant height and basal area in defining the timing and intensity of thinning. This means that whenever a given upper limit for the basal area (thinning threshold) at the given dominant height is encountered, thinning could be triggered (Figure 2, Paper II). Thinning was carried out in this study from below and trees were removed to such an extent that the remaining basal area was reduced to the expected value as regards the dominant height.

Thus, the timing of thinning is adjusted to the growth and development of the tree population in such a way that thinning will occur just before mortality, due to crowding. Thinning was applied when the dominant height $\geq$ 12 m. Prior to this, trees may die due to crowding. Random mortality was applied for the whole simulation. The values of the basal area triggering the thinning and the remainder after thinning may be combined in many ways. Therefore, a preliminary analysis was done in order to limit the number of the thinning regimes to a reasonable number.

A total of 25 stand treatment programmes (STPs) were constructed by first changing the basal area remaining after thinning by 0%, ± 15% and ± 30% with no change in the thinning threshold. The basal area for the thinning threshold was then changed by 0%, ± 15% and ± 30%; the remaining basal area varied in the same way as above. In addition, simulations representing no thinning were carried out, with only a clear cut at the end of the simulation period. The analysis showed that only a limited number of STPs were reasonable in terms of total production; i.e. the total growth was not less than that with current practices. Furthermore, regimes with an excessive number of thinnings with a small volume of harvested timber were excluded. Only STPs with a higher remaining basal area alone or concurrently with a higher upper limit triggering the thinning fulfilled these criteria (Papers I, II, IV). Two more scenarios, which only reduced the remaining basal area by 15% and 30%, were kept for sensitivity purposes **(**II). In total, for this part of the study, eight STPs for each tree species (seven thinning regimes and one unthinned) were accepted for further analyses**.** The simulation on the two sites covers a fixed period of one hundred years, with clear-cut taking place at the end of simulation period (Paper I) or even before it if the average breast height diameter of trees exceeded 30 cm, which indicated the maturity for regeneration (Paper II).When clear-cut takes place earlier than at the end of the maximal length of the simulation period, the site is regenerated by planting with the same species prior to the clear cut.

Climate scenarios

The simulations employed three different climate scenarios; one which was the current climate and two transient climate change scenarios (Table 2). The current climate (CRU) scenario is represented by data from the period 1961-1990, with the CO_2 concentration held constant at a level of 350 ppm. The HadCM2 scenario for a changing climate follows the prediction derived from the Hadley Centre Global Circulation Model (Sabaté et al. 2002, Mitchell et al. 2004). The ECHAM4 climate change scenario is based on data generated by a general circulation model originally developed by the Max Plank Institute, Hamburg, Germany (Roeckner et al. 1996).

Both climate scenario data sets have been compiled by the Potsdam Institute for Climate Impact Research (PIK), Germany. The seasonal variations in the current climate (over the period 1961-1990) and the climate conditions under the climate change (during the period 2071-2100) are shown in Paper II, Figure 4. The CO_2 concentration of the climate change scenarios was nearly doubled linearly from 350 ppm to 653 ppm by the end of the simulation period. The data for these scenarios were based on the greenhouse emission scenario IS92a (Houghton et al. 1992).

3. RESULTS

3.1. Stand level impacts of management and climate scenarios on growth and timber yield (I)

Sensitivity of model outputs to environmental conditions and management

The role of the sensitivity analysis was to better understand how the climate change and management affects on growth response of trees. It was found that the increase in temperature in northern Finland enhanced substantially the total growth regardless of tree species, while any changes in precipitation affected only marginally. In southern Finland, Scots pine was less affected (2.5 – 4.9% increase) by any change in temperature and/or precipitation compared to silver birch (3.8 – 9.4 % increase) and Norway spruce (2.5% increase). In the latter one, the concurrent reduction of precipitation with high increase in temperature reduced substantially the growth.

With the doubling of CO_2, Scots pine enhanced its growth by 25 – 35% regardless of precipitation or site as linearly related to the temperature increase. In the south, the doubled CO_2 compensated the growth reduction occurring, when the largest increase in temperature (+5^{o}C) and the largest reduction in precipitation (-20%) coincided at the 350ppm CO_2 concentration.

The response of Norway spruce in the south was around 26-27 % increase with both an increase in temperature and precipitation, and it presented a decrease related to the increase in temperature and a decrease in precipitation. In the north for this species the response was maximum with the highest increase in temperature and precipitation, and the increase was minimum with a temperature increase and a maximum decrease in precipitation. Silver birch in the south, presented an increase when temperature was increased concurrently with increase in precipitation, but a decrease in precipitation yielded no visible change; in the north the behaviour of this species was similar to Scots pine with a maximum increase up to 21%

Nitrogen increase enhanced growth in Scots pine by 11 – 13%, and more in the north than in the south. This response was fairly similar for any combination of the changes in temperature and precipitation regardless of the site. Norway spruce also experienced increases but to a lower level, specially when the precipitation was decreased, regardless of the site. Silver birch presented a higher increase in the south compared to the north, where the response was around 5% regardless of the combination in climatic parameters.

Regardless of the site and tree species, thinning increased the amount of precipitation per remaining tree and the soil moisture along with the increasing thinning intensity. The increase was larger in the north than in the south regardless of the tree species. Under all thinning regimes, mortality amounted up to 9% of total growth; i.e. the largest values represented silver birch and the smallest ones the conifers, with no major difference between Scots pine and Norway spruce (Paper I, Tables 5-7). These values represented the mortality during the early phase of development, before the first thinning. Under no thinning (UT(0,0))), mortality was 30-50% of total growth, as expected.

Effects of changes in climate scenarios and stand treatment programmes(STPs)

On average for the STPs, the climate change increased the growth of Scots pine by 28% in the south and by 54% in the north. For Norway spruce, the increase was smaller than that for Scots pine; i.e. 24% in the south and 40% in the north. The response of silver birch was smaller than that of conifers; i.e. growth increased by 21% in the south and 34% in the north. The enhanced growth implied an increase in the timber yield regardless of tree species and site.

Over the thinning regimes, the mean increase in timber yield for Scots pine was 26% in the south and 50% in the north. For Norway spruce, the increase was somewhat smaller, i.e. 23% in the south and 40% in the north. For silver birch, the increase was the smallest, i.e. 20% in the south and 33% in the north. The STPs had a clear effect on total growth and timber yield. Any thinning regime increasing the mean stocking over the rotation increased the total growth and timber yield regardless of the tree species and site. Most notably the unthinned scenario presented the highest increase in growth but the lowest yield, and the BT(+30,+30) the highest growth after UT(0,0) and the highest timber yield, respectively.

3.2. Stand level impacts of management and climate scenarios on carbon stocks in the forest ecosystem and in harvested timber (II)

Carbon in the forest ecosystem

Under the current climate, the carbon stock was regardless of tree species and sites clearly largest if thinnings were not applied (i.e. UT(0,0) used). For example in Scots pine, it was up to 30 - 40% higher compared to that obtained under the Basic Thinning regime (BT(0,0)). Stand treatment programme BT(+30,+30) gave, an increase of 12 - 9%, compared to the Basic Thinning (from 95 Mg C ha^{-1} to 106 Mg C ha^{-1}in the south and from 72 Mg C ha^{-1} to 79 Mg C ha^{-1}in the north). Heavy thinning, on the other hand, appeared to reduce the carbon stock (Table 3, II). Compared to Scots pine, the carbon stock was in Norway spruce stand an average clearly larger (Table 3, II), although thinnings affected similarly for both species. Stand treatment programme UT(0,0) gave in Norway spruce up to 52% higher carbon stock in the south and 36% higher in the north compared to that obtained under the Basic Thinning regime (BT(0,0)). However, stand treatment programme BT(+30,+30) was able to increase the carbon stock in Norway spruce only by 7 - 9% compared to the Basic Thinning (from 172 Mg C ha^{-1} to187 Mg C ha^{-1} in the south and from 148 Mg C ha^{-1} to 159 Mg C ha^{-1} in the north). As a comparison to Scots pine and Norway spruce, the carbon stock under the Basic Thinning regime was in silver birch 40% less in the south and 30% less in the north than that under UT(0,0). Whereas it was under the stand treatment programme BT(+30,+30) it was 10 - 9% larger than that under the Basic Thinning regime for south and north respectively.

In general, both climate change scenarios applied were found to increase the carbon stock in the forest ecosystem regardless of tree species and sites. This was mainly due to the increased tree growth. Enhancement of litter production in comparison to the decomposition of litter and soil organic matter further increased the accumulation of carbon (Figure 5, II). In the south, the increase was up to 6 – 7% regardless of tree species and climate scenario. The increase was, however, clearly higher in the north; i.e. 13 - 17% in Scots pine, 8 - 9% in Norway spruce and 10 - 12 % in silver birch stands, depending on the climate scenario.

The increase in the carbon stock tended, however, to be in some degree larger under the ECHAM4 (which simulated a larger temperature and precipitation increase) than under the HadCM2 regardless of sites, tree species and stand treatment programme. Under climate change, the impacts of thinnings on the carbon stock followed, however, the same pattern as that found under the current climate regardless of sites. In general, higher stocking of tree stands increased the growth, and consequently the carbon stock in the forest ecosystem.

Carbon in harvested timber and its relation to increased stocking

Under the current climate, the carbon stock in harvested timber (fresh harvested timber) increased with changes in the thinning threshold regardless of tree species and sites. For example, in the south, in Scots pine and Norway spruce the carbon stock in harvested timber was 18 -20% higher under the stand treatment programme BT(+30,+30) compared to Basic Thinning regime (Table 6, II). In Norway spruce, unthinned stand treatment programme UT(0,0) also increased in some degree unexpectedly the carbon stock in harvested timber by 17% compared to the Basic Thinning. This was because in unthinned stands the stocking was kept at higher level than in thinned stands over the rotation and the maturity for final cutting was achieved later than in thinned stands.

In silver birch, same tendency was observed in thinning treatments as in conifers, but the carbon stock decreased in unthinned stand treatment programme UT(0,0). In short, the simulations indicated that thinning programmes, which kept the stocking of tree population higher over rotation, increased the carbon in timber yield, compared to the current practices, regardless of tree species and climate scenario. The climate change in itself enhanced carbon stocks regardless of tree species and management, and more in the north than in the south.

The simulations demonstrated also that carbon sequestration in the forest ecosystem may be enhanced with no loss in timber production even under the current climate by modification of the current management practices.

Concerning the stand treatment programs with regular thinnings, the timber yield correlated also positively with the carbon stock in the forest, in such a way that in Scots pine and silver birch an increase of 1 Mg C ha^{-1} in the mean carbon stock will yield an increase of about 2 Mg C ha^{-1} in the timber production. In the case of Norway spruce, the sensitivity of carbon stock in regard to timber yield is much smaller (Figure 7, II).

3.3. Utility analysis of alternative management programmes under climate change (IV)

Distribution of stochastic utility simulations under current climate and mean utility under different climate scenarios

Simulations over a planning period of 100 years under current and changing climate scenarios by a physiological growth model provided input data for the stochastic multi-criteria analysis of forest management alternatives. For Scots pine and Norway spruce, under the current climate, the range of utility values for many of the stand treatment programmes tended to overlap to some extent (Paper IV Figure 5). Nevertheless, it is evident that high utility was simulated only for a few of them used in the analysis, notably BT(+30,+30) and UT(0,0). The utility obtained at the northern site was considerably lower, compared to the southern site.

In southern Finland, the utility values in silver birch were substantially smaller than in Norway spruce and Scots pine stands nonetheless. The no thinning treatment (UT(0,0)) covered a broader range of utilities than the other treatments. The overlapping of the utility range demanded a more aggregated index for analysis under both current climate and climate change.

In the above context, mean utility was used further as an indicator to identify the overall best stand treatment programme for different tree species. For Scots pine growing in the south, BT(+30,+30) was the option that best satisfied all objectives regardless of the climate. At the northern site, UT(0,0) yielded the highest utility under current climate and BT(+30,+30) under both climate change scenarios. For Norway spruce growing in the south (Paper IV, Table 6), BT(+30,+30) had on average the highest utility, regardless which climate scenario was used. At the northern site, under the current climate and the HadCM2 climate change scenario UT(0,0) ranked first in terms of mean utility. Under the ECHAM4 scenario, BT(+30,+30) was the most preferable. In southern Finland, UT(0,0) was in silver birch the stand treatment programme, which produced the highest average utility under the current climate (CRU), while BT(+30,+30) was best one under the climate change scenarios (Paper IV, Table 7). At the northern site, UT(0,0) was the most preferable option in terms of utility regardless of the climate scenario.

Effects of changing climate on total expected utility

Over two sites and three tree species compared, only two out of eight stand treatment programmes were able to dominate the set of alternatives; namely UT(0,0) and BT(+30,+30) in which stocking was kept at higher level compared to the currently recommended guidelines regardless of sites and tree species. Applying Eq. (3) for the aggregation of utilities under different climate conditions, this can be interpreted as the expectation value of overall utility with weight parameters c(l) as subjective probabilities of occurrence of a particular climate scenario.

For Scots pine growing in the south, UT(0,0), BT(0,0) and BT(+30,+30) increase the expected utility at a similar rate with decreasing weight of CRU, clearly indicating the favourable effects of a warmer climate as represented by ECHAM4 and HadCM2 (Figure 6A, IV). At the northern site, utility in general also increases with decreasing weight of CRU, with UT(0,0) (with the highest utility) and BT(+30,+30) being more preferable than BT(0,0).

However, at a weight for CRU of about 0.30, BT(+30,+30) and UT(0,0) changed rank, implying an improvement in the utility if BT(+30+30) is implemented under climate change (Figure 6B, IV). For Norway spruce at both sites, the utility follows the tendency to increase with decreasing weight of CRU (Figure 6C, 6D, IV). For silver birch growing in the south, the trend of increasing utility at lower weights for CRU is maintained (Figure 6E). When current climate is considered more likely (i.e., a higher weight is assigned), UT(0,0) is the stand treatment programme with the highest utility and BT(+30,+30) when climate change is more likely. At the northern site, there is no change in the rank order for this species, i.e. UT(0,0) provides highest utility (Figure 6F, IV).

Probability of 1st rank as indicator of preferentiality for stand treatment programmes and effects of reduced uncertainty on decision criteria

The probability of each stand treatment programme to be on the first rank as affected by uncertainty in priorities for partial objectives and criteria and by the weight of the climate scenarios is evaluated here (Figure 7, IV). In southern Finland, Scots pine with BT(+30,+30) is ranked first in all of the 1000 replicates, regardless of the weight assigned to the climate scenarios. For Norway spruce, the result is very similar. Silver birch shows a somewhat contrasting response to the applied preference information: i.e. with increasing weight on CRU the probability of UT(0,0) increases strongly until it reaches a probability of first rank of 0.76 at full weight on current climate in the south. At a weighing factor of 0.75 for the current climate, BT(+30,+30) and UT(0,0) show equal probability of being the most preferable stand treatment programme in silver birch. Interestingly, a similar behaviour is found in Scots pine at the northern site, where UT(0,0) and BT(+30,+30) share equal probabilities to be the best STP at a weighing factor of 0.3 for CRU. The ranking of stand treatment programmes for silver birch growing in the north, is almost completely insensitive to varying weight for the climate scenarios having exclusively UT(0,0) on first rank. For Norway spruce, UT(0,0) and BT(+30,+30) share equal probabilities of first rank at a weight of 0.1 for CRU in northern Finland. With increasing weight given on the current climate UT(0,0) increases probability of first rank.

A relevant issue is whether a reduction of parameter uncertainty itself may reduce uncertainty in calculating expected utilities. In this study, reducing uncertainty (by assuming accurate weights for the criteria) did not show any large changes in expected utility. For Scots pine and silver birch, and at both sites, the probabilities of first rank were almost completely insensitive to the reduced uncertainty in the weight vector. Norway spruce was the only tree species that showed a change in the results but the magnitude was nevertheless small, i.e. uncertainty was reduced by 5-10% assuming perfect knowledge of the criteria weightings.

4. Discussion and conclusions

Forests provide different kind of services to communities in terms of conservation, biodiversity, watershed and soil protection, as well as recreation in addition to timber production. To these services it could be added "carbon forestry", emphasising the important role of forests and their management for maintaining carbon stocks and enhancing forest sink capacity for carbon (Jarvis et al. 2005).

In the above context, this study investigated based on stand level simulations by a process-based ecosystem model how management and climate change affect the growth, timber yield and carbon stocks in boreal forest ecosystem. In addition, it was studied how the management affects under varying climate the possibility to meet multi-purpose demands in regard to timber production, carbon sequestration and biodiversity (in terms of dead wood) based on a stochastic multi-criteria analysis. For this purpose, it was used different stand treatment programmes, which differed from each other in the sense that mean stocking in the tree populations over the rotation was increased or decreased compared to that applied currently. This allowed the identification of how sensitive growth, timber yield and carbon stocks are to the management and the climate change. The first part of this study (Paper I) focused on the effect of climate change on total growth of Scots pine, Norway spruce and silver birch, with consequent effects on the total timber yield.

Concerning the climate change, the simulations showed that an increase in temperature and precipitation with a concurrent elevation in CO_2 may enhance growth in boreal forests by 24- 53%, depending on the tree species and site. The increase is, however, smaller in the south than in the north. Under the climate change, the total timber yield increased also along with the increase in growth, i.e. an increase of 20-40% was obtained depending on tree species and site compared to that under the current climate. The increase was clearly larger in the north than in the south, where the absolute timber yield was still larger than in the north regardless of the tree species.

The main finding of the sensitivity analysis in regard to effects of management was that regardless of the tree species and site, an increase in the thinning threshold increased the total growth and timber yield relative to the levels obtained with the Basic Thinning. This tendency was further enhanced if the remaining basal area was increased concurrently with the increase in the threshold for thinning. Thus, higher stocking kept over rotation did not lead to losses in terms of timber yield. The simulations showed that both the level of growth and the volume of harvestable timber are likely to increase throughout Finland, and that the current thinning guidelines might not be optimal for management under the altered conditions. As a result, the necessity to develop adaptive management strategies to climate change is underlined in this study.

To conduct an analysis of carbon stocks in forest ecosystem and in harvested timber (Paper II), the same two sites and initial conditions for the stands were used as in Paper I. A minor modification to clear-cut criteria was used, however. As an alternative to the end of the simulation period (100 years) as clear-cut threshold, it was also used an average diameter in the stand of 30 cm regardless of tree species and sites. The results from the simulations indicated that an increase in the stocking of the tree population enhanced the mean carbon stock compared to the current recommended guidelines for management over the rotation. This tendency was valid for each tree species, sites and climate scenarios used in the simulations. These findings demonstrate that the carbon stocks in the forest ecosystems can be increased by applying a proper thinning regime without any prolongation of the rotation, which has been considered to be the most efficient way to enhance the carbon sequestration in forestry (e.g. Read et al. 2001, Seely et al. 2002, Kaipainen et al. 2004).

The stocking obtained with stand treatment programme which increase the stocking the highest (BT(+30,+30)) although larger than in BT(0,0) was still low compared to that obtained without any thinning (UT(0,0)). This suggests that the stocking in managed forests could possibly be increased even further beyond the 30% tested, which was found most efficient in terms of carbon stock among the selected thinning regimes used in this study.

This study proves the importance of analyzing changes in the thinning thresholds, where there are no empirical data to inform decision makers. As forests are extensively managed in Finland, it would be feasible to introduce new management alternatives, as the ones here exemplified, parallel to those currently recommended even under conditions of current climate. The usefulness of the results here presented can serve as a guide to forest managers and other decision makers, to assess what kind of opportunity costs (in terms of production and carbon sequestration) would be incurred if no change in management guidelines is taken, even under current climatic conditions. The current thinning practices which aim to maximize the amount of large-dimension timber (saw logs) through low stocking may underestimate the potentials of forests in terms of carbon sequestration.

This is in line with the findings of Thornley and Cannell (2000), who concluded that management regimes mimicking natural forest disturbance are likely to provide a combination of high timber yield and carbon storage. It is, however, unrealistic to expect forests to be managed solely for their effect on carbon emissions (Seely et al. 2002) since management will continue to be guided by traditional economic benefits.

However, a number of management strategies are no-regret options, increasing the amount of carbon without experiencing looses in timber production (Humphreys and Palo, 1998). As shown here, high stocking throughout the rotation may be preferable in order to enhance the carbon sequestration in the forest ecosystem and also to enhance the timber production. Having this in mind it is necessary to study the effect that many management objectives would have when they are considered parallelly.

The first two papers (I, II) demonstrated the capacity of the forests stand to grow under climate change conditions, produce given amounts of timber and to act parallelly as carbon sinks in an array of management alternatives. However, there can be more management objectives included which would have different overall implications for management. Thus, the overall goal for the last part of the study (Paper IV) was to evaluate the performance of the new stand treatment programmes for boreal forests in Finland, with regard to multi-objective forest management under conditions of climate change. This was done, by combining the possibilities of process-based modelling (capable for simulating the growth and dynamics of tree under varying environmental conditions) and management and additional software (WPM-IS) developed in Paper III (used to calculate the carbon storage in the wood products pool). In this context, the state and flow variables as simulated by the process-based model were used as decision criteria in a hierarchical additive utility model developed in Paper IV. Considering that the public perception on the relative importance of management objectives will most likely always be heterogeneous, it was analysed whether a specific stand treatment programme is preferred over the complete weight space as defined by the weight distributions. Thus, the multi-criteria analysis was run as a Monte Carlo simulation with 1000 random replicates of the full weight vector of the utility model.

However, no quantitative data from a specific opinion poll among forest stakeholders was used for this study. Instead, qualitative information was utilized (, Finnish Ministry… 1999, Yrjölä, 2002, Rantala et al. 2003) to define probability distributions for each weight parameter in the utility model. Biodiversity was particularly difficult to analyse due to the ample criteria used in its measurement. As a definition biodiversity is a general term that refers to the variety of forms of life found in a particular location, which can be evaluated in terms of different types of biological structures present (Fürstenau et al. 2006). The use of deadwood for a biodiversity criterion is based on the fact that is a quantifiable variable which can be simulated, by the FinnFor model for a single species stand. The use of deadwood has been used to assess ecological values in several past and present studies (Kangas and Pukkala 1996, Schuck et al. 2004, Fürstenau et al. 2006). A certain amount of deadwood is necessary to provide habitat for species depending on deadwood. Lower amount of deadwood is one key issue in most forests, where saproxylicorganisms tend to be especially vulnerable (Lindhe 2004). For all their benefits however, unmanaged forest reserves and set-aside areas are of limited value for many species. Such forests produce little of the sun-exposed dead wood favoured by most saproxylic beetles adapted to natural disturbances. Some studies in the early nineties however, indicated that disturbance-adapted beetles may also utilize dead wood on logging sites in managed forest landscapes (Lindhe 2004).

Another interesting issue was the combination of utilities from three different climate scenarios applied, considering the weight parameters of the climate scenarios as subjective probabilities. This approach may be interpreted as an expectation value for overall utility. One of the most interesting result was that the Basic Thinning regime BT(0,0), currently the recommended, was never among the most preferred stand treatment programme. Surprisingly, at all sites and for all species the unthinned scenario UT(0,0) has the capacity to attain higher utility than the BT(0,0). In this instance it is important to note that BT(0,0) was designed purely with timber production goals in mind (Liski et al. 2001, Yrjölä 2002).

Obviously there is the need to design and improve stand treatment programmes that include not only timber related management objectives but explicitly address goals such as carbon sequestration, biodiversity and, thus, calls for a multi-purpose forest management. Among the eight analysed stand treatment programmes, BT(+30,+30) clearly dominates concerning NPV; UT(0,0) with regard to carbon storage in the forest ecosystem and also deadwood. From this follows, depending on the weight vector, that one of these two ones will be the best treatment. The differences in utility for these cases can be set off by higher carbon storage in the forest and much higher deadwood of UT(0,0), but low NPV compared to the other stand treatment programmes under current climate. Under the climate warming, the capacity to produce sawn timber increases substantially. Consequently, the results in a rank is reversal for UT(0,0) and BT(+30,+30) with regard to the mean expected utility and the probability of first rank. The finding of this study clearly demonstrates that forest management has to be adaptive to changing environmental conditions in order to avoid non-optimal silvicultural stand treatment.

The effect of reduced uncertainty on the overall preferentiality of stand treatment programmes was also tested. For Scots pine and silver birch the effect is negligible. In the north, solely for Norway spruce a clear effect can be observed, increasing the probability of first rank for the unthinned treatment scenario without major changes in the general utility pattern. Finally, it is worth noting that the preference functions are one additional potential source of uncertainty. In the current study, they had been assumed as certain. The preference functions were based on the data set extracted from the simulations and kept as simple as possible.

In summary, it is concluded that the combined use of forest ecosystem models and multi-criteria analysis are an appropriate means to analyse the performance and preferentiality of forest management alternatives. Taking into account the uncertainties in forestry decision making will result in improved and more reliable decision support. In this study, it was shown that even when quantitative data on involved uncertainties are lacking and considerable uncertainty is allocated to the weight parameters, the use of qualitative information on objective and criteria weights may allow the identification dominant alternatives. A general finding was that management in boreal forests can be an efficient way to benefit from a warmer climate. Without adapting forest management to changing environmental conditions the potential benefits of a warmer climate may not be realized. Similarly, changing stakeholder needs and preferences on how forests should be managed greatly determine the potential overall utility generated by alternatives, and consequently their ranking with regard to expected utility might change. Another conclusion from this study is that timber production and carbon sequestration together are not conflicting management objectives if the proper management is applied under current climate and changing climatic conditions; and that even including other aspect such as biodiversity it is still possible to increase total utility for the conditions mentioned. However, it must be recalled that all these findings were derived to medium fertility sites with young seedlings stands used as initial stand conditions for simulations. Therefore, it is important to study in the future more in details also the impacts of management and different climate scenarios on real stands growing on varying site conditions and comprising different age and development classes, in order to have full understanding how these findings can be generalized over larger areas.

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ANNEXES

Annex Table1.

Table A1. Flow parameters of the Wood Products Model-IS European version. Sources and sinks are indicated. Number of sinks is referred to the level which the flow of carbon is directed into.

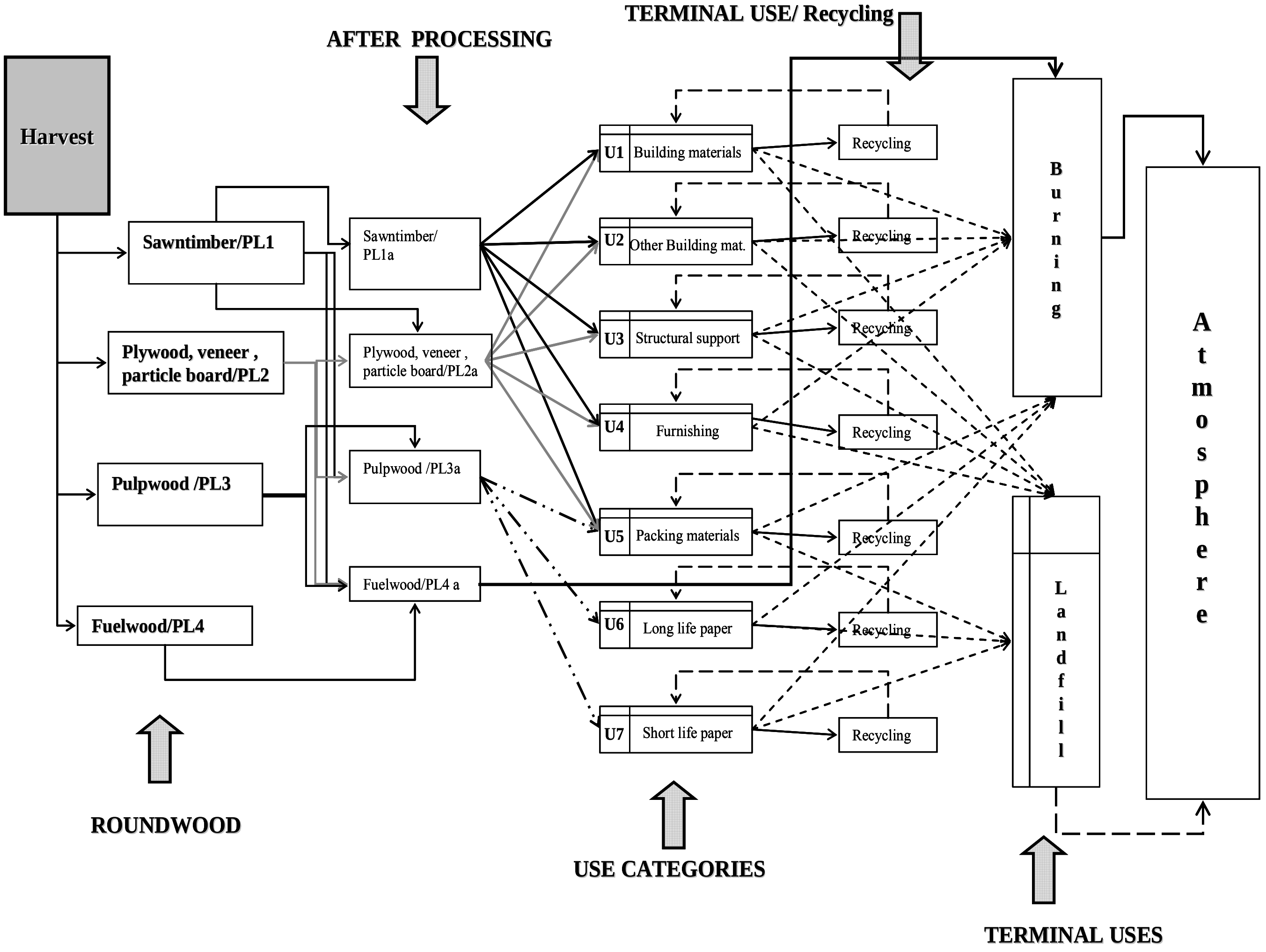
Linking of state variables **source**	**#of sinks**	**sink**	**Flow parameter value**	**[%]**
PL1	4	PL1a	0,435	43,5
		PL2a	0,000	0,0
		PL3a	0,435	43,5
		PL4a	0,130	13,0
PL2	3	PL2a	0,537	53,7
		PL3a	0,210	21,0
		PL4a	0,254	25,4
PL3	2	PL3a	0,700	70,0
		PL4a	0,300	30,0
PL4	1	PL4a	1,000	100,0
PL1a	5	U1	0,350	35,0
		U2	0,300	30,0
		U3	0,100	10,0
		U4	0,150	15,0
		U5	0,100	10,0
PL2a	5	U1	0,125	12,5
		U2	0,175	17,5
		U3	0,200	20,0
		U4	0,250	25,0
		U5	0,250	25,0
PL3a	3	U5	0,335	33,5
		U6	0,330	33,0
		U7	0,335	33,5
PL4a	1	BURN	1	100,0
U1	3	rU1	0,300	30,0
		BURN	0,350	35,0
		LAND	0,350	35,0
U2	3	rU2	0,250	25,0
		BURN	0,250	25,0
		LAND	0,500	50,0

Continue….

Continue TableA1…..

U3	*3*	*rU3*	*0,150*	*15,0*
		BURN	0,400	40,0
		LAND	0,450	45,0
U4	3	rU4	0,250	25,0
		BURN	0,250	25,0
		LAND	0,500	50,0
U5	3	rU5	0,360	36,0
		BURN	0,320	32,0
		LAND	0,320	32,0
U6	3	rU6	0,360	36,0
		BURN	0,320	32,0
		LAND	0,320	32,0
U7	3	rU7	0,360	36,0
		BURN	0,320	32,0
		LAND	0,320	32,0
rU1	1	U1	1	100
rU2	1	U2	1	100
rU3	1	U3	1	100
rU4	1	U4	1	100
rU5	1	U5	1	100
rU6	1	U6	1	100
rU7	1	U7	1	100
BURN	1	ATM	1	100
LAND	1	ATM	1	100

Source: Karjalainen et al 19945, Eggers 2002.



Annex Figure 1. Structure of the Wood products model used in this study. European Version.