Potential Energy Wood Production with Implications to Timber Recovery and Carbon Stocks Under Varying Thinning and Climate Scenarios in Finland

Ashraful Alam · Antti Kilpeläinen · Seppo Kellomäki

Abstract An ecosystem model (Sima) was used to investigate the impact of climate and varying thinning regimes concurrently on energy wood and timber production as well as on growth and carbon stocks during 2010–2099 in southern (below 64° N) and northern (above 64° N) Finland. The analysis was carried out using sample plots from the ninth National Forest Inventory. According to the results, both energy wood and timber production increased under the changing climate, with this effect being found to be higher in northern compared to southern Finland. In relative terms, the effect of forest structure, however, was more pronounced than that of climate, especially in southern Finland. Increased basal area thinning thresholds enhanced carbon stocks compared with current thinning regime. In addition, increased thinning thresholds enhanced concurrently energy wood production (at final felling) and timber production during the period 2040–2069 and merely energy wood production (at final felling) during 2070–2099. In absolute terms, the production potential of energy wood at energy wood thinning was found to be higher in northern compared with southern Finland, but the case was opposite at final felling both in current and changing climate. It was concluded that a concurrent increase in energy wood and timber production as well as carbon stocks would be possible in Finnish forests if thinning was performed at a higher tree stocking level than in the current recommendations.

Keywords Climate change · Ecosystem model · Energy wood production · Thinning regime · Timber production and carbon stocks

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Introduction

Responding to the challenge of climate change, the European Commission has set an ambitious target to increase the share of renewable energy in the total energy consumption of the EU from 8.5% (2005) to 20% by 2020 [1]. Finland (60–70° N, 19–32° E) is one of the leading countries in the EU regarding the use of wood-based energy, where it is the second largest energy source, covering one fifth of the country's total energy consumption [2]. A major part (ca. 11%) of this energy is from by-products and black liquor produced by forest industries. Furthermore, energy wood (e.g. forest and industrial chips, bark and sawdust) consumed in heating and power plants covers ca. 7% and in small-sized dwellings ca. 3% of the total energy consumption [2].

The use of wood-based energy may produce several benefits, which include offsetting greenhouse gas emissions from the combustion of fossil fuels, utilisation of locally available raw materials [3–6] and to some extent, reducing carbon emissions owing to the decomposition of forest residues left after final felling (FF). In Finland, the use of energy wood in energy production has garnered growing attention as it could help in the implementation of the Kyoto agreement. Several attempts have been taken aiming to promote and increase the share of renewable energy sources of the overall energy production [7, 8]. For example, Finland's 'National Forest Programme 2015' aims to increase the use of forest chips in energy generation from 3.4 million m^3 in 2006 to 8–12 million m^3 by 2015 [7] and a recent 'National Climate and Energy Strategy' [9] approved by the Finnish Government aims to increase the share of renewable energy to 38% by 2020.

In Finland, based on size and quality criteria, timber is assorted into sawlogs and pulpwood for industrial purposes

using the cut-to-length method. Total timber consumption in Finland during 2006 was 81.5 million m^3, over 90% of this, or about 76 million m^3, was used by forest industries [2]. About 21 million m^3 was utilised to generate energy, of which 15% came from forest chips and 30% from round wood with the remainder coming from the combustion of bark, sawdust and industrial chips from the sawmilling and plywood industries [2]. Forest chips are still a relatively modest source of fuel, but it has extensive growth potential [10]. A potential source of forest chips consist of branches and crown mass harvested from commercial thinnings and FF, i.e. tree components that do not fulfil the requirement for industrial use, including poor quality timber, stem tops, living and dead trees and stumps. In addition to these, small-sized trees are harvested for energy use in energy wood thinning (EWT) and pre-commercial thinning [10, 11].

Several studies have estimated the potential recovery of above and below ground energy wood raw materials in Finland. Hakkila [10] estimated that, depending on the cost limit, the maximum technically harvestable energy wood potential is 16 million m^3 year^{-1}, which is about 35% of theoretical potential estimated from all above and below ground biomass residues from a hypothetical annual stem wood removal of 70 million m^3. In the study of Asikainen et al. [12], potential annual felling residues were estimated to be about 24 million m^3, where they included stem wood loss, branches, tops, needles, stumps and roots as biomass components. A study for the whole of southern Finland by Malinen et al. [13] found that the economically feasible potential of energy wood that could be harvested was estimated to be a maximum of 8.8 million m^3 year^{-1} over a 40-year period. In their study, energy wood consisted of logging residues from FF, branches, bark residues and stem wood from first commercial thinning.

Forests in Finland are likely to experience considerable changes in the future due to the changing climatic conditions. In a boreal ecosystem, low temperature, short growing season and limited availability of nitrogen are considered to be limiting factors regarding forest growth [14–17]. Changes in climate, as defined by an increase in temperature and CO_2 and changes in precipitation patterns [18–20], may imply a higher decomposition rate of organic matter [21–23], which may lead to more nutrients being available for the trees. These changes are likely to increase growth, enhance forest productivity [24] and change the structure (e.g. species composition) and functioning of boreal forest ecosystems [15, 25–32]. Accordingly, Bergh et al. [33] found an increase of ca. 240% in energy wood production from logging residues under climate change from current production of 3.1 Tg year^{-1}. The similar increasing trend (ca. 30%) was also found by Kärkkäinen et al. [34] between current and changing climatic condition,

however, the magnitude of projected changes was less compared with the study by Bergh et al. [33] because of shorter projection period.

In order to cope with the changing conditions, the expected climate change may add a new dimension to the business-as-usual forest management. It has been suggested that impacts of climate change on European forests (including Finland) necessitate the modification of the business-as-usual management to mitigate the unfavourable effects [35] and to optimally utilise increased growth in energy wood [33, 34] and timber production [30, 36, 37] and also in enhancement of carbon stocks in the forest ecosystem. EWT, earlier and/or more intensive commercial thinning and resulting shortened rotation periods with decreased self-thinning of tree stands, could be effective measures to utilise the increased productivity under climate change with regard to energy wood and timber production [38–40], whereas the effects on carbon stocks might be opposite [41].

The role of forests to mitigate climate change and produce energy wood concurrently with timber and carbon stocks may change objectives of forest management in the future. Management intervention together with varying environmental conditions should be considered for different forest types and structure of the forests (young or mature stage). This will identify not only the determinants of the production potential of forests but also possibilities in mitigating climate change. Earlier, we have studied the thinning and climate effects on growth, timber production and carbon stocks in the forest ecosystem in Finland [42], based on previously available National Forest Inventory (NFI 8) data and climate scenarios. In the present study, we utilised the newly available forestry datasets (NFI 9) and new climate scenarios and investigated the impacts of varying thinning regimes and expected climate change on production and fossil fuel substitution potential of energy wood (small-sized trees in EWT and logging residues in FF) with implications to concurrent production of timber (sawlogs and pulpwood) and development of carbon stocks in the forest ecosystem (trees and soil) over the whole Finland.

Materials and Methods

Ecosystem Model (Sima)

Outline of the Model

In the utilised model, the dynamics of the forest ecosystem, as regulated by demographic processes (regeneration, growth, and death), is assumed to be determined by the dynamics of the number and mass of trees. All these

processes are related to the availability of resources and regulated by the canopy gap dynamics of the tree stand. The model and its parameterisation and validation is exhaustively described elsewhere [43–46] and therefore only an outline of the model is presented here.

The model utilises four environmental subroutines describing the site conditions that affect the growth and the development of forests, i.e. temperature, light, moisture and availability of nitrogen. The environmental subroutines are linked to the demographic subroutines by the multipliers (M); i.e. $G = G_o \times M_1 ... M_n$, where G is growth and/or regeneration, G_0 is growth and/or regeneration in optimal conditions meaning that there is no shading and no limitation of soil moisture and supply of nitrogen, and $M_1 ... M_n$ are multipliers for different environmental factors (Fig. 1). In addition, in the case of growth, the values of G_0 are assumed to be related to the maturity of the tree (diameter of tree) and the prevailing atmospheric CO_2, furthermore the parameterisation of the growth response is also species-specific. The data for the G_0 calculation are based on the simulations of a physiological growth and yield model applying the same methodology than Matala et al. [47]. In these simulations, the growth of a single tree with an ample supply of water and nitrogen was calculated under varying atmospheric CO_2 concentrations and under no shading for the conditions in southern Finland.

In the model, mortality is determined by factors that are either age-dependent or age-independent. Age-dependent mortality is a stochastic event depending on maximum age of a tree. In the case of age-independent mortality, the probability of tree death at a certain moment increases with decreasing diameter growth due to competition from other trees. After dying, trees are eliminated from among the living trees and immediately converted to litter, which is linked directly to the decomposition subroutine and included in the nitrogen cycle.

The model is parameterised for Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L. Karst.), silver birch (*Betula pendula* Roth.), downy birch (*Betula pubescens* Ehrh.), aspen (*Populus tremula* L.), and grey alder (*Alnus incana* Moench., Willd.) growing between the latitudes 60° N and 70° N and longitudes 20° E and 32° E within Finland. The model utilises an area of 100 m² with a 1-year time step.

Input Data

The data utilised in the model was based on the NFI 9 (1996–2003). The measurements in the inventory were done from systematically located rectangular or L-shape clusters, each cluster containing 10–18 sample plots. The distance between the clusters varied from 6×6 km in the southernmost part of the country to 10×10 km in Lapland (Fig. 2). In establishing sample plots, the Bitterlich concepts were used and the tally trees were selected using a relascope. The probability of the inclusion of a tree was proportional to its diameter at breast height (dbh), where maximum radius of 12.52 m was used [48–50].

For our study, data from one sample plot from each cluster was used to represent variables such as tree species, dbh, site type, location and temperature sum. In addition, the simulations included only sample plots in upland mineral soil sites (Fig. 2). As each measured tree in a sample plot stands for a certain number of trees depending on its diameter, inclusion of them were done accordingly into the simulations. However, the inclusion of large diameter trees into the simulations was done by using a combination of different diameter classes of

Fig. 1 Outline of the model used in this study
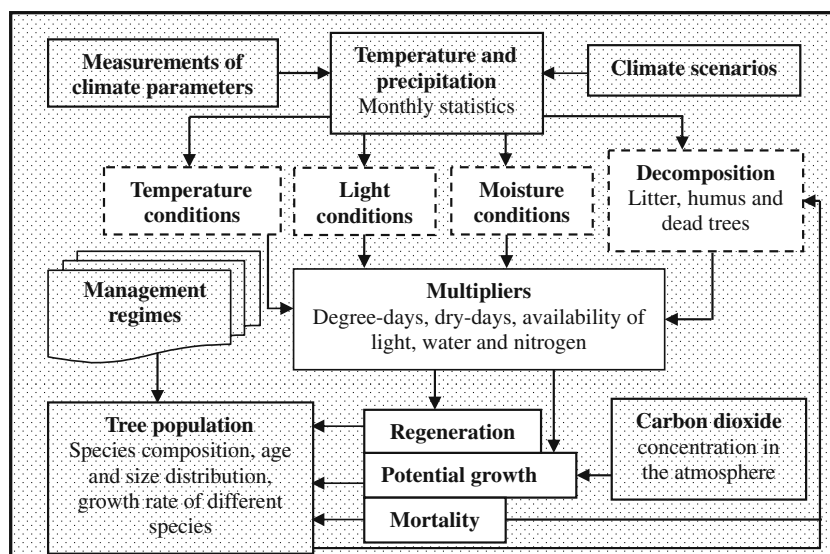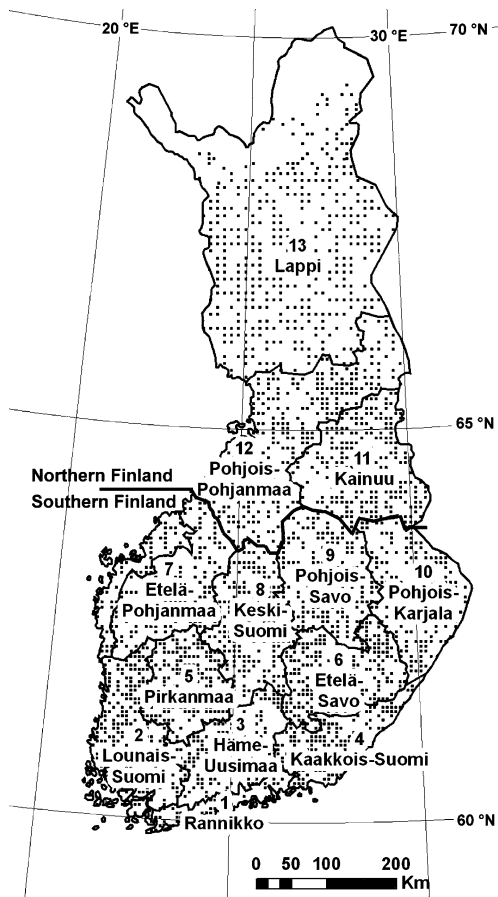
Fig. 2 Sample plots used in this study (*dots*), forestry centres (*numbers*) and separation in northern and southern Finland (*thick line*)

large trees. Due to the model structure (use of 100 m² area), diameter classes were combined so that the number of trees was as close to 100 as possible. Accordingly, in the case of small-sized trees, the number of stems was limited to 3,000/ha.
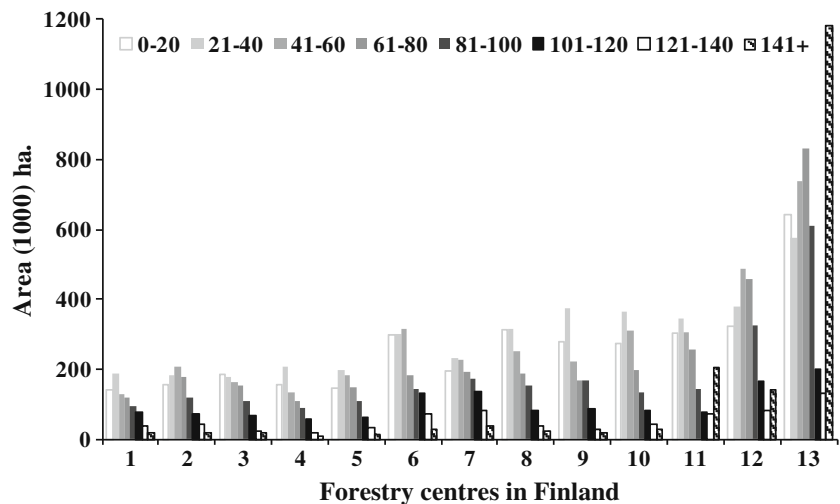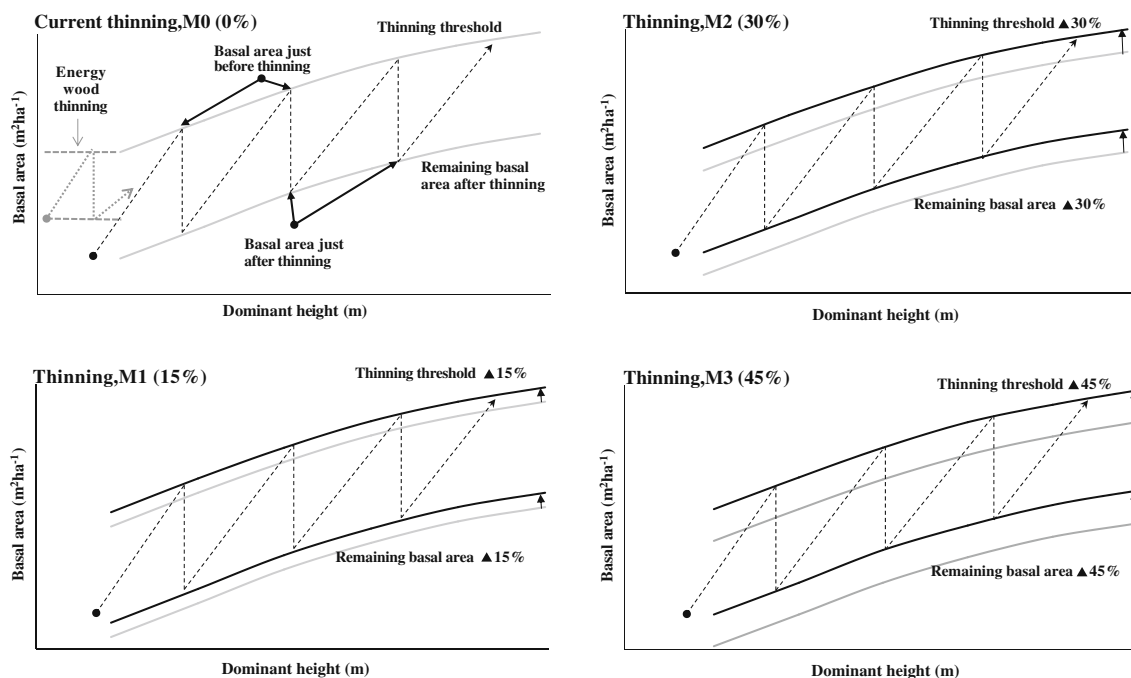
According to the NFI data, forests are mainly in young stage in all the forestry centres located in south, but the share of older forests is higher in northern Finland [2] (Fig. 3). Soils in Finland are generally more fertile in the south than in the north [51, 52]. Species composition, therefore, differs among the site classes. Pine is mostly dominating the less fertile sites i.e. *Vaccinium* type and *Cladonia* type. While Norway spruce, together with birch, is dominating the most fertile sites, i.e. *Oxalis-Myrtillus* type. However, the medium site class, *Myrtillus* type, is suitable for (or a mixture of) Norway spruce, birch and Scots pine [26].

Forest Management Scenarios

In the simulations, management includes EWT, commercial thinning, FF and regeneration. The thinning rules followed those currently recommended for the different tree species, site types and regions of Finland (southern and northern Finland separately) [53]. Whenever a given upper threshold for the basal area was encountered at a given dominant height, commercial thinning was triggered (Fig. 4). Thinning was done from below, to such a level that the remaining basal area was reduced to the expected value at a given dominant height [53]. In the case of executing EWT, tree dominant height of between 8–14 m was used, with the lower threshold being determined by following the recommended remaining number of trees dependent on site and species [53] (Fig. 4).

The FF was made whenever the mean diameter of the trees in the plots exceeded the given value indicating the maturity of the tree population for regeneration. On the other hand, the FF can be done whenever the time since the previous regeneration felling (rotation length) exceeded a given value [53]. In regeneration, a combination of natural regeneration and planting was utilised in the simulations. The tree species

Fig. 3 Forest age-class (20 years) distribution in respect to area occupied in forestry centres in Finland, from South to North (1–13) [2]

Fig. 4 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 the current thinning regime, M0 (0%)

that were present in the stand before regeneration would occupy the stand either with same species or following species-specific thresholds in environmental factors.

In general, these management rules are seldom applied systematically. This has led to a situation characterised by increased stocking due to cuttings being less than the increment. This is the case especially in southern Finland, where cuttings are often delayed compared to those suggested by the management rules. Consequently, simulations using the current management rules led to excessive cutting removal and a large reduction of stocking at the beginning of the simulation. Therefore, the deterministic application of the management rules was replaced by a random procedure.

Whenever the management rules indicate thinning or FF for a stand, a random number r (0...1) was selected, and its value was then compared to the value of the parameter p. If $r<p$, no cutting was executed. The value of $p=0.95$ was selected. This meant that the mean delay (x) for cutting was 13 years compared with that indicated by the management rules (Eq. 1). As a result of the delay, the simulated cuttings were comparable with the business-as-usual management currently applied in Finnish forestry, since there were no major changes in the stocking at the beginning of the simulation [46].

$$p^x = 0.5 \Rightarrow x = 13 \text{years} \qquad (1)$$

In addition to the current thinning, three other thinning regimes were selected for this study by changing both the

basal area thinning thresholds compared to business-as-usual; 15% (M1), 30% (M2) and 45% (M3). These were suggested by the authors according to earlier findings [42]. The current recommendations were considered as a base, business-as-usual, thinning (M0) (Fig. 4). The thresholds for EWT were always similar for the different thinning regimes.

Climate Scenarios

The simulations utilised climate data provided by the Finnish Meteorological Institute. Scenarios for the climate projection are averages of responses calculated using nineteen global climate models, where variables such as minimum and maximum temperature, precipitation, solar radiation, air pressure, snow depth, soil moisture and wind velocity have been analysed [54, 55]. The grid for current climate (1971–2000) was 10×10 km, however the model used in this study applied it in a 50×50 km grid. The climate change scenarios were in three tri-decadal periods i.e. near-term, 2010–2039, mid-term, 2040–2069 and long-term, 2070–2099 and used the same grid size applied in model as current climate. The certainty regarding the level of climate change was stronger for the first two projection periods compared with the final period, which includes major uncertainties in predictions due to the development of global greenhouse gas emissions for different scenarios and considered more as an example of probable climatic condition at the end of this century. This study utilised the

A2 scenario [56], where CO_2 concentration was estimated to rise to 840 ppm by 2100 and temperatures were projected to increase, for example, by 7.6°C for January and 3.4°C for July over the whole of Finland. In winter, warming was strongest in the north, while in summer the more pronounced warming would be in the south of the country. Correspondingly, by 2100 precipitation was estimated to increase by about 30% in the winter and about 10% in late summer [54, 55].

The data for the current climate and the climate change scenarios represented the daily values. Based on these the monthly mean temperature and the monthly mean precipitation, both with standard deviation, were calculated over the periods applied in the context of the model. In the case of the climate scenarios, the mean temperature and precipitation represented the mid-point of the period used in the model. The values between the mid-points are based on a linear interpolation between the values at two consecutive mid-points. In the simulations for a given sample plot, the calculation algorithm utilised the climate in the closest grid point of the climate data.

Computations

The analyses of climate and thinning regimes impact focused on energy wood, growth, timber and carbon stocks in three 30-year periods during 2010–2099 in Finland. The growth in the calculations refers to the mean annual increment of the growing stock over the each studied 30-year period. The concept of timber production here refers to the production of sawlogs and pulpwood. The part of the stem with a minimum top diameter of 15 and 6 cm refers to sawlogs or pulpwood, respectively, the remainder of the stem represents logging residues.

Energy wood consists of both small-sized trees from EWT and logging residues (branches and tops of the stem, large roots and stumps) from FF. The dry weight of large roots, in the context of the utilised model, was calculated via allometric relationship with dbh, while the stumps were calculated as a function of stem wood. Energy wood, in this study, was focused on the potentiality and may deviate from what is technically harvestable or available for recovery. Carbon stocks refer to the carbon in stems, branches, leaves and roots in the trees in the growing stock and in the ground vegetation and forest floor (decaying wood, litter and humus) including standing dead trees according to the outputs of the utilised model. Initial values of litter and humus layer were used in initialising the simulation as a function of site type and temperature sum [46].

The calculations were done to get absolute values of energy wood (Mg ha^{-1} year^{-1}), growth (m^3 ha^{-1} year^{-1}), timber (m^3 ha^{-1} year^{-1}), and carbon stocks (Mg C ha^{-1}) for all the thinning regimes under current climate (CU) and

changing climate (CC). Therefore, comparisons focused on either the effect of climate or effect of thinning regimes under CU and CC. To be able to produce the effect of climate, corresponding thinning regimes under CC were compared with CU. The effect of thinning was compared only with the current thinning and this was done both for current and changing climatic conditions.

Apart from above simulations, controlled simulations were done to separate the effects of climate and forest structure on forest growth during the whole simulation period (2010–2099). The outcomes of these simulations are shown in the last section of the results. In these simulations, the forest structure was kept constant according to initial data (based on the NFI 9) at the start of each 30-year period (2010-2039, 2040–2069, 2070–2099) and simulated until the end of each period both under current and changing climatic condition. Eventually, the results from business-as-usual structure were compared with the results of these controlled simulations.

In all cases, comparisons of scenarios were always done with corresponding output periods. For example, the outputs of the first period (i.e. 2010–2039) under CC were compared with outputs from the CU for the same period.

Results

Effects of Climate and Thinning on Energy Wood Production

Recovery at Energy Wood Thinning

In general, the energy wood production at EWT (small-sized trees) increased over time both for CU and CC in southern as well as in northern Finland. During the first period (2010–2039), neither increased basal area thinning thresholds, compared with current thinning regime, nor climate change, did affect the energy wood production at EWT, either in southern or northern Finland. During period two (2040–2069), increased basal area thresholds did not affect the energy wood production at EWT, neither in southern nor in northern Finland but climate change increased energy wood production at EWT both in southern and northern Finland. In both southern and northern Finland, during the last period (2070–2099), climate change increased the energy wood production at EWT but increased basal area thresholds increased the energy wood production at EWT only under CC (Fig. 5a, b).

Recovery at Final Felling

The energy wood production at FF (branches, large roots, stumps and tops of the stem) was higher during the second

Fig. 5 Effects of thinning on energy wood production at energy wood thinning (*EWT*) (**a** and **b**) and final felling (*FF*) (**c** and **d**) in three 30-year periods between 2010–2099 under current climate (*CU*) and changing climate (*CC*) in southern and northern Finland. M0 (0%) represents current thinning regime. The scale of the EWT in the south (**a**) is smaller than that of EWT in the north (**b**)
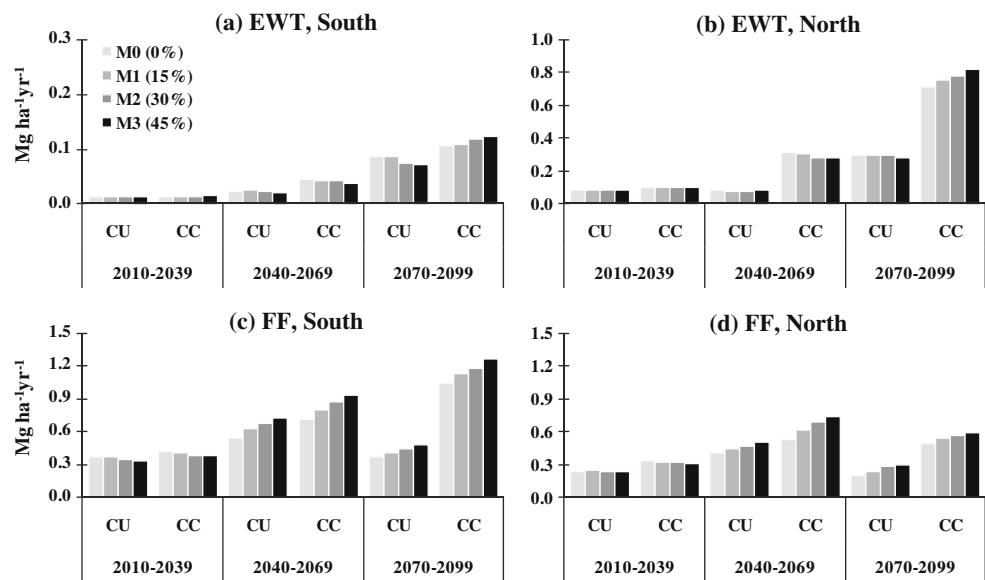
period (2040–2069) compared with first period (2010–2039) under both CU and CC in southern as well as in northern Finland but it was highest during the third period (2070–2099) under CC in southern Finland. During the first period (2010–2039), both in southern and northern Finland, increased basal area thinning thresholds, compared with current thinning regime did not affect the energy wood production at FF under CU and CC, but climate change increased the production at FF. During the second and last period, both climate and increased thinning thresholds enhanced the energy wood production at FF both in southern and northern Finland (Fig. 5c, d).

Effects of Climate and Thinning on Growth, Timber Production and Carbon Stocks

In general, the climate change increased growth (growing stock increment), timber production (sawlogs and pulpwood) and carbon stocks in the forest ecosystem (trees and soil) in both southern and northern Finland in all the three periods (2010–2039, 2040–2069, 2070–2099). The changes were similar for all the thinning regimes, but they varied between southern and northern Finland (Fig. 6).

During the first period (2010–2039), under CU and CC, increased basal area thinning thresholds enhanced growth, compared with current growth of 5.7 and 3.0 m^3 ha^{-1} $year^{-1}$ in the current thinning regime in southern and northern Finland respectively (Fig. 6a, b). During the same period, increased thinning thresholds increased carbon stocks in the forest ecosystem for both CU and CC in southern and northern Finland (Fig. 6e, f), but this reduced timber production both in south and north under CU and CC (Fig. 6c, d). In both southern and northern Finland, during the second period (2040-2069), growth, timber production and carbon stocks were increased with increased thinning

thresholds in either CU or CC. During the last period (2070–2099), increased thinning thresholds enhanced growth and carbon stocks regardless of regions and climate scenarios, but timber production was increased only under CC in northern Finland (Fig. 6).

Separated Effects of Climate and Forest Structure on Forest Growth

According to the controlled vs. business-as-usual forest structure simulations, the effect of forest structure on forest growth, in relative terms, was more pronounced than that of climate (Fig. 7). The effect of climate was found to be higher in the north (forestry centres 11–13) than in the south (forestry centres 1–10), whereas the effect of structure was the opposite both under CU and CC. In addition, there was no structure effect found during the first period (2010–2039) owing to have a similar structure at the beginning of the simulation and development of growing stocks in that period.

Discussion

This study focused on the effects of energy wood (small-sized trees and logging residues) due to climate change and varying thinning regimes with implications on growth (growing stock increment), timber (sawlogs and pulpwood) and carbon stocks (trees and soil) in Finland. In the simulations, the parallel effect of climate change, in terms of temperature, precipitation and CO_2 increase, were studied. Risks, for example related to insects attack, wind throw, forest fire and frost damage related to climate change were not included in the analysis of this study.

Fig. 6 Effects of thinning on growth (growing stock increment) (a and b), timber production (sawlogs and pulpwood) (c and d) and carbon stocks in the forest ecosystem (trees and soil) (e and f) in three 30-year periods between 2010 and 2099 under current climate (CU) and changing climate (CC) in southern and northern Finland. M0 (0%) represents current thinning regime
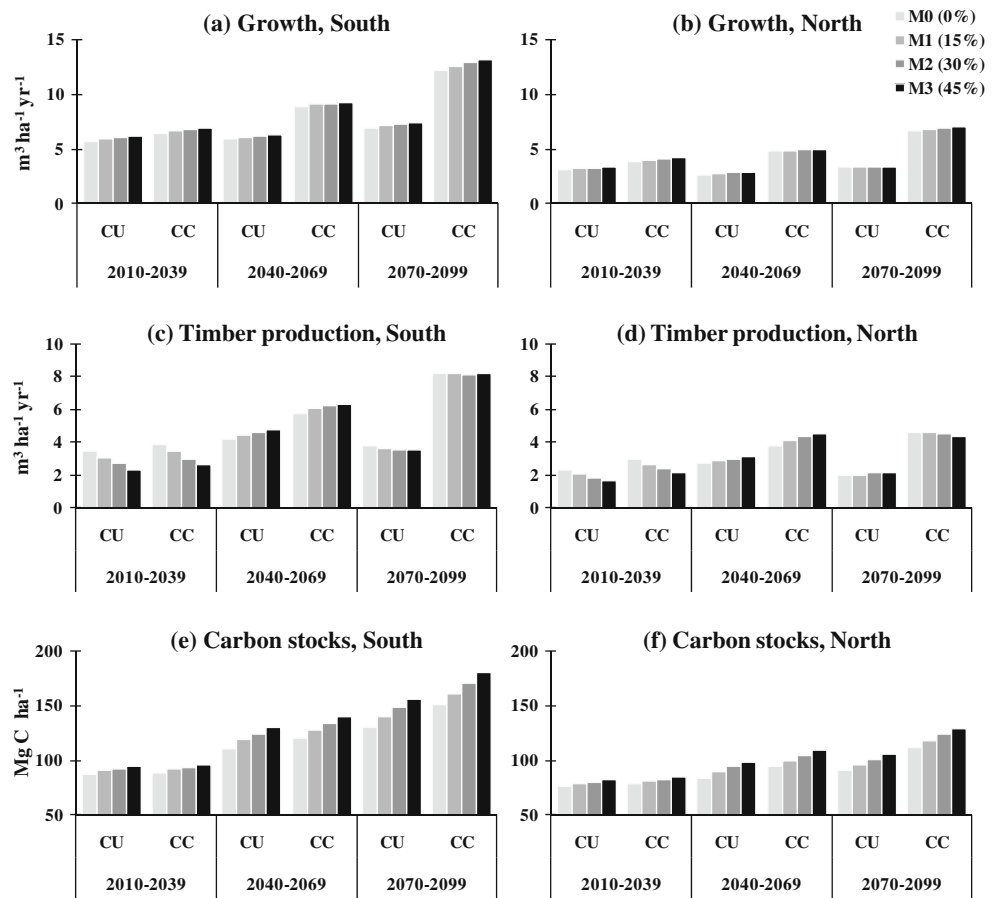
Under CU and current thinning regime, the production of energy wood at FF (ca. 6.6 Tg year^{-1} or 16 million m^3 year^{-1}) during the first period (2010–2039) had lower values than those estimated by Hakkila [10], Asikainen et al. [12] and Kärkkäinen et al. [34]. This might be a result of the different cutting scenarios, logging residues components and their recovery at varying thinning stages. Thus, results from those studies may not directly be comparable with our findings. For example, poor quality timber as energy wood raw material and energy wood extraction (logging residues) in all the commercial thinnings, were not considered in this study

as was done by Kärkkäinen et al. [34]. Moreover, our study used a mean delay of 13-year period between the cuttings in order to have consistency of the stocking at the beginning of the simulation, which was not taken into consideration in other studies [10, 12, 34]. As the production of energy wood at FF was converted to usable energy, this study found 60 and 100 MWh ha^{-1} (40 and 68 TWh year^{-1}) in current thinning regime under CU and CC, respectively (Table 1). However, part of the estimated energy wood production is affected by practical limitations, so that the results should be considered as theoretical potentials.

Fig. 7 Effect of climate and forest structure on forest growth (growing stock increment) in three 30-year periods between 2010 and 2099 in 13 forestry centres (see Fig. 2) of Finland. Effect of structure is given under current climate (CU) and changing climate (CC). The three periods are shown either in *bars* or in *symbols* (error marks, empty triangles)
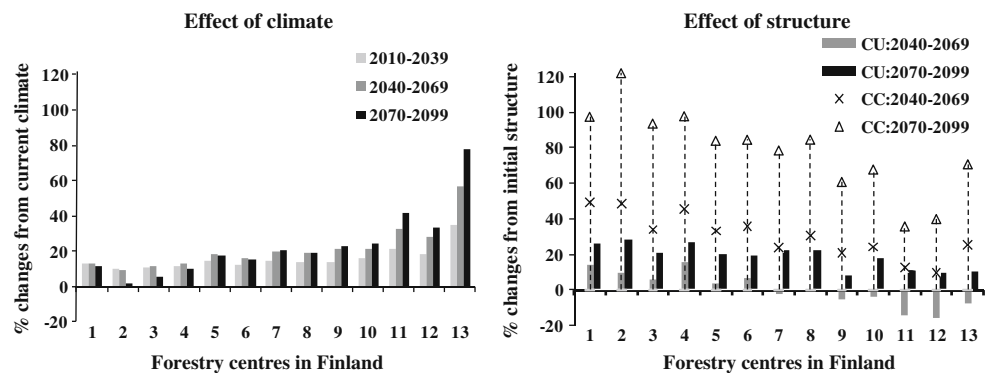
Table 1 Effects of thinning on production and fossil fuel substitution potential of energy wood in energy generation in Finland derived from EWT (energy wood thinning) and FF (final felling) over the whole simulation period (2010–2099)

Thinning regimes	Current climate				Climate change			
	Energy wood thinning	Final felling	Total		Energy wood thinning	Final felling	Total	
	MWh ha^{-1} year^{-1}			%	MWh ha^{-1} year^{-1}			%
M0 (0%)	0.43	2.00	2.43	–	0.88	3.34	4.22	–
M1 (15%)	0.43	2.17	2.60	7	0.90	3.60	4.49	6
M2 (30%)	0.41	2.29	2.71	11	0.91	3.77	4.68	11
M3 (45%)	0.40	2.41	2.81	16	0.94	3.97	4.91	16

M0 (0%) represents current thinning regime. Effective heating value at 20% moisture content on fresh mass basis: 19.23 GJ/t (energy wood thinning) and 19 GJ/t (final felling) [57]. 1GJ=0.2778 MWh

The potential production of energy wood at FF was higher in southern Finland compared to northern Finland, which might be due to the effect of timber production in those regions. On the contrary, energy wood production at EWT was higher in northern than in southern Finland. These dissimilarities in productions were mainly the result of variation in forest structure and growth potential in southern and northern Finland. Currently, in the south, the forests are dominated by young stands, while, in the north, stands are more mature or close to that stage (Fig. 3) [2]. Therefore, with the development of the forests both in northern and southern Finland, the energy wood production was enhanced in the second (2040–2069) and third (2070–2099) periods compared with the first period (2010–2039).

When thinnings were done according to current management recommendations, this study found a 5% smaller forest growth under current climate during the first period (2010–2039) than that found in the Finnish NFI [2]. This smaller growth might be due to the utilisation of only upland sites on mineral soils in the simulations. However, this study found that increased tree stocking after thinning (or increased basal area thinning thresholds) enhanced growth regardless of climate scenarios, periods and location. Higher tree stocking after thinning may, however, decrease individual tree growth as a result of competition for limited resources. Accordingly, timber production was reduced during the first period (2010–2039) implying that thinning at higher tree stocking delayed cuttings [58, 59]. This had also effect on energy wood production at FF, which was reduced associated with reduction in timber production, where it was increased in the later phases of the simulations (i.e. 2040–2069 and 2070–2099).

The concurrent analyses of energy wood, timber and carbon stocks showed that a concurrent increase in them was possible at the same time, during the second period (2040–2069), where they increased with enhanced level of basal area thinning thresholds. In the case of timber and carbon, this is in well agreement with the findings of Briceño-Elizondo et al. [29], Garcia-Gonzalo et al. [60], and Thornley and Cannell [61], where they concluded that management with higher tree stocking, but also with continuous canopy cover and fewer disturbances throughout the rotation could give maximum production of timber and carbon stocks. However, Seely et al. [41] suggested a trade-off between ecosystem carbon storage capacity and timber production, which was found also in this study during the first and last periods. The earlier study done by the authors [42] had also a similar trend, where former NFI data and climate scenarios were utilised. Nevertheless, in all cases, increased thinning thresholds enhanced carbon stocks in the forest ecosystem under CU and CC, as could be expected due to an increase in growing stocks.

The results showed that, compared with CU, forest growth increased considerably in Finland under changing climatic conditions. The largest relative changes were found in northern Finland, although values in absolute terms were higher in southern Finland. Our study also showed a greater relative effect of forest structure on growth than that of climate change (Fig. 7). This change in growth was higher in southern than in northern Finland, which was opposite to the effect of the climate. This was a result from varying initial forest structures in different parts of the country. However, the effect of climate was in line with other findings in boreal conditions [e.g., 30, 42, 62] where a corresponding increases in growth under the climate change were found. Garcia-Gonzalo et al. [32] reported also that initial age class distribution may not be the same at the end of 100-year simulation period even if there is equal distribution at the beginning of the simulation. That could be owing to management intervention in the forests during the rotation period. Therefore, management activities and varying growth rate have profound and prolonged effects on forest structure and composition [32, 63, 64].

Conclusions

Higher growth rate and thus increase of carbon uptake and production in forest ecosystems under climate change may provide new objectives and opportunities for forest management. In our case, it was possible to enhance the growth and concurrently increase energy wood and timber production mainly in the second period by increasing tree stocking from the current level. Otherwise there was a trade-off among energy wood, timber and carbon stocks. At the same time, higher carbon stocks were still maintained throughout the simulation period if the tree stocking was increased. The interaction between forest management and climatic conditions has not only a vital role in maintaining forest growth in forest ecosystems, but also it is highly relevant to energy wood production for fossil fuel substitution, integrated with timber production and carbon storing in the context of climate change mitigation. In the future optimally combining all these factors to fulfil their objectives might not be possible without modifying the current forest management.

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