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Effects of forest management and climate change on energy biomass and timber production with implications for carbon stocks and net CO_2 exchange in boreal forest ecosystems

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Academic dissertation

To be presented, with the permission of the Faculty of Science and Forestry of the University of Eastern Finland, for public examination in the Auditorium BOR100 of the University of Eastern Finland, Yliopistokatu 7, Joensuu, on 17th May 2011, at 12 o'clock noon.

Title of dissertation: Effects of forest management and climate change on energy biomass and timber production with implications for carbon stocks and net CO_2 exchange in boreal forest ecosystems

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Dissertationes Forestales 117

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ISSN 1795-7389
ISBN 978-951-651-324-2 (PDF)

(2011)

Publishers:
Finnish Society of Forest Science
Finnish Forest Research Institute
Faculty of Agriculture and Forestry of the University of Helsinki
School of Forest Sciences of the University of Eastern Finland

Editorial Office:
Finnish Society of Forest Science
P.O. Box 18, FI-01301 Vantaa, Finland
http://www.metla.fi/dissertationes

Alam, A. 2010. Effects of forest management and climate change on energy biomass and timber production with implications for carbon stocks and net CO_2 exchange in boreal forest ecosystems. Dissertationes Forestales 117. 30 p.
Available at: http://www.metla.fi/dissertationes/df117.htm

ABSTRACT

The aim of this work was to investigate the effects of forest management and climate change on energy biomass (wood) and timber production with implications for carbon stocks and net CO_2 exchange in boreal forest ecosystems in Finland. First, the impacts of thinning on growth, timber production and carbon stocks under the current and changing climate were analysed by employing an ecosystem model for the whole of Finland over a 90-year period (Article I). Concurrently, the potential of energy biomass production with implications for timber production and carbon stocks under varying thinning and climate scenarios was studied (Article II). Thereafter, a life cycle assessment (LCA) tool for estimating net CO_2 exchange of forest production was developed (Article III), and it was applied in interaction with ecosystem model based simulations to study the impacts of different management regimes (initial stand density and thinning regimes) on energy biomass production and related CO_2 emissions at a stand level with a rotation length of 80 years (Articles III & IV).

The results showed that the climate change increased the production potential of energy biomass and timber, and carbon sequestration and stocks over the whole of Finland, but, in a relative sense more in northern than southern Finland (Articles I & II). Decreasing basal area based thinning thresholds compared to the currently recommended ones, increased the harvesting of the annual average amount of timber compared to the annual average growth of stem wood, and reduced carbon stocks in the forest ecosystems (Article I). On the other hand, the use of increased basal area thinning thresholds concurrently increased energy biomass and timber production, and carbon stocks in the forest ecosystem regardless of climate applied (Article II). The development of the LCA tool made it also possible to estimate the net carbon exchange of the forest production (Article III). Based on the use of the LCA tool with the ecosystem model simulations, it was found that the impacts of management related emissions on net carbon exchange were small compared to the total ecosystem fluxes. It was also found that the increase in initial stand density compared to the conventional practice of 2000 seedlings ha^{-1}, not only increased the energy biomass production at energy biomass thinning, but also reduced management related CO_2 emissions of energy biomass production (Article IV).

To conclude, the applied management substantially affects the net atmospheric impacts of production potential of forest ecosystems. The combined use of ecosystem model simulations and the LCA tool will together provide new insights for the analysis of ecologically sustainable energy biomass and timber production systems and the climate change mitigation options of forests.

Keywords: Boreal forests, climate change, ecosystem model, energy biomass, forest management, net CO_2 exchange

ACKNOWLEDGEMENTS

This thesis work was funded mainly by the Nordic Energy Research (NER) through the project 'The Climate and Energy Systems; Risks, Potential and Adaptation – Renewable Energy: Biofuels co-ordinated by Prof. Seppo Kellomäki, School of Forest Sciences, University of Eastern Finland and partly by the European Union through the project 'METSÄENERGIA' (Project No. S10363) under sub-project B: Metsäbiomateriaalien tuotanto ja tuotannon ympäristövaikutusten hallinta' also lead by Prof. Seppo Kellomäki. Additionally, part of the study was funded by the University of Eastern Finland. Furthermore, I got grant from the Finnish Cultural Foundation for finalising the thesis work. I thank and deeply acknowledge all of the funding sources to complete the work. I also acknowledge the support provided by Graduate School of Forest Sciences.

I express my deepest gratitude to my supervisors, Prof. Dr. Seppo Kellomäki and Dr. Antti Kilpeläinen, from the University of Eastern Finland (Joensuu), Finland, for their commitment, support and continuous guidance throughout the research work. Without their expert guidance and consistent suggestions, it would have been difficult to complete and present the work. In addition, Mr. Harri Strandman is greatly appreciated for his constructive contribution as a co-author in Article III and help in solving the technical problems during the model simulations throughout the work.

I express my special indebtedness to Docent Dr. Heli Peltola from the University of Eastern Finland (Joensuu), Finland, and Prof. Dr. Kai-Yun Wang from the East China Normal University (Shanghai), China, to be follow-up members/mentors of my thesis and for their encouragements and suggestions whenever needed. I am also grateful to the official reviewers of this thesis, Prof. Anti Asikainen and Dr. Jordi Garcia-Gonzalo for their valuable comment and constructive criticism. Dr. David Gritten is acknowledged for improving the language of the thesis. Special thanks to all of my colleagues and friends (in Finland or abroad), who have always been supportive throughout the study.

I am highly grateful to my parents (Nurul Amin and Razia Amin), brothers (Lappy and Mishu), sister (Ajmira) and all relatives for their continuous inspiration and co-operation. Last but not the least; I would like to express my sincere gratitude to my beautiful wife Liza for her continual support during this study and my adorable daughter Liyana to be always my inspiration and encouragement. Love you Liyana.

Joensuu, April 2011

Ashraful Alam

LIST OF ORIGINAL ARTICLES

This thesis is based on the following four Articles, which will be referred in the text by Roman numerals, I–IV. The Articles I–III are reprinted with the kind permission of the publishers or with the right retained as author, while the Article IV is the author version of the submitted manuscript.

I. Alam, A., Kilpeläinen, A. & Kellomäki, S. 2008. Impacts of thinning on growth, timber production and carbon stocks in Finland under changing climate. Scandinavian Journal of Forest Research 23: 501–512.
doi: 10.1080/02827580802545564

II. Alam, A., Kilpeläinen, A. & Kellomäki, S. 2010. Potential energy wood production with implications to timber recovery and carbon stocks under varying thinning and climate scenarios in Finland. BioEnergy Research 3: 362–372.
doi: 10.1007/s12155-010-9095-1

III. Kilpeläinen, A., Alam, A., Strandman, H., & Kellomäki, S. 2011. Life cycle assessment tool for estimating net CO_2 exchange of forest production. Global Change Biology Bioenergy. In print.
doi: 10.1111/j.1757-1707.2011.01101.x

IV. Alam, A., Kilpeläinen, A. & Kellomäki, S. 2011. Impacts of initial stand density and thinning regimes on energy wood production and management related CO_2 emissions in boreal ecosystems. Submitted manuscript.

Ashraful Alam had the main responsibility for analysing and writing the Articles I, II & IV. The co-authors participated in formulating the research tasks and commenting on the manuscripts. In Article III, Ashraful Alam participated in the writing and analysis equally with the other co-authors.

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ABBREVIATIONS

A2	IPCC Climate change scenarios (increase in temperature and carbon dioxide concentration, and changes in precipitation pattern)
a^{-1}	Per year
BP	Integrated bioenergy (energy biomass) and timber production regime
C_{decomp}	Carbon dioxide emissions from soil litter and humus decomposition
C_{harv}	Carbon dioxide emissions from harvested timber and energy biomass
C_{man}	Carbon dioxide emissions from management operations
C_{net}	Net carbon dioxide exchange
C_{seq}	Carbon dioxide uptake into forest biomass
CO_2	Carbon dioxide
CT	*Cladonia* site type
EBT	Energy biomass thinning
EU	European Union
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
ISD	Initial stand density
LCA	Life cycle assessment
m^3	Cubic metre
MT	*Myrtillus* site type
NFI	National Forest Inventory
OMT	*Oxalis-Myrtillus* site type
TP	Traditional timber production regime
VT	*Vaccinium* site type
Mg	Megagram
MWh	Megawatt hour (1 MWh=3.6 GJ, Giga joule)
Tg	Teragram
TWh	Terawatt hour

1 INTRODUCTION

1.1 Boreal forest ecosystems, climate change and forest management

Forests in Finland (60˚–70˚ N, 26˚–19˚ E) are of the boreal type, occupying an area of 26.3 million ha, corresponding to approximately 86% of Finland's total land area (Peltola 2009). A large share, 80%, of these forests are dominated by coniferous tree species such as Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.), with the remaining 20% being dominated by deciduous species, mainly silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescens* Ehrh.). The majority of these forests grow on areas classified as forest (annual increment ≥ 1 m^3 ha^{-1}) and scrub (annual increment from 0.1 to 1 m^3 ha^{-1}) land (Peltola 2009). Over the whole of Finland, the annual increment of stem wood is nowadays, on average, 100 million m^3, while the annual removal (up to 70 million m^3 in the last few decades) is clearly lower than it (Peltola 2009). In general, forest growth decreases towards the north due to the variability of climate and structure of forests between northern (above 64˚ N) and southern (below 64˚ N) Finland. Low summer temperatures, short growing season and availability of nitrogen are mainly affecting the forest growth rate in the boreal forest ecosystems (Linder 1987, Kellomäki et al. 1997, Mäkipää et al. 1998a,b, Jarvis and Linder 2000). Low temperatures also reduce the decomposition rate of organic matter (Moore et al. 1999, Berg 2000, Karhu et al. 2010) and limit the availability of nitrogen in the soil.

Changes in climate, as defined by an increase in temperature and carbon dioxide (CO_2) concentration and changes in precipitation patterns, could generate complex responses by the boreal forest ecosystem (Mandre et al. 1996, Talkkari 1998, Kellomäki et al. 2008). In Finland, the future climate is expected to be characterised with an increase of 2–7ºC in annual mean temperature and 6–37% in precipitation related to a doubling of CO_2 by 2100 (Jylhä et al. 2004, Carter et al. 2005, Ruosteenoja et al. 2005, Ruosteenoja and Jylhä 2007). These changes are likely to increase the growth of boreal forests directly through physiological processes in trees, but also through longer growing seasons and increasing mineralisation of nitrogen (e.g. Kellomäki et al. 1997, Black et al. 2000, Lasch et al. 2002, Bergh et al. 2006, Briceño-Elizondo et al. 2006a, Garcia-Gonzalo et al. 2007a,b, Kärkkäinen et al. 2008). Furthermore, owing to the changes in growth, species composition and functioning of the boreal forest ecosystem will also be affected in the long run. Thus, the unique characteristics of the boreal forest ecosystem make them particularly susceptible to the likely upcoming climate change (IPCC 2007).

Likewise changing climatic conditions, also forest management (e.g. changes in intensity and timing of thinning) will affect the growth and development of the forest stands due to the changes in the available resources for the remaining trees after management interventions. However, expected increase in growth of boreal forests due to warmer climate may make it necessary to adapt the current, business-as-usual, management in terms of timing and intensity of thinning, for example. This could be needed in order to fully utilise the positive effects of climate change, such as increased forest productivity and carbon sequestration in the forest ecosystems (e.g. Parry 2000, Lindner 2000, Lasch et al. 2005, Bergh et al. 2006, Briceño-Elizondo et al. 2006a,b, Nuutinen et al. 2006, Kärkkäinen 2008).

1.2 Energy biomass production and utilisation

In Finland, the forests have traditionally been managed with first priority for timber production. However, environmental concerns, responding to human induced global warming, have recently lead to the realisation that the utilisation of other tangible and intangible forestry services must also be included as additional forest management objectives. As a response, exploring the potential of energy biomass production and how to integrate its production in forest management practices is getting much attention at present (Hoen and Solberg 1994, Ahtikoski et al. 2008, Kärkkäinen et al. 2008, Heikkilä et al. 2009). Current forest management practices aiming mainly at timber production may not necessarily be appropriate as such for the integrated production of energy biomass and timber and also for increasing the carbon sequestration and stocks in the forest ecosystem. In the future, there may also be a need to adapt forest management to provide different ecosystem services such as energy biomass and timber, and carbon sequestration in forest ecosystems in a sustainable way.

It has been previously shown that increased rotation length could result in the larger storage of carbon in the forest ecosystem (Karjalainen 1996, Liski et al. 2001, Pussinen et al. 2002, Kaipainen et al. 2004). However, it may simultaneously reduce the availability of timber for industrial purposes (Seely et al. 2002). Many previous studies have tried to find a solution on how the carbon stocks of forest ecosystems can be increased during a rotation period without reducing the potential of forests for timber production. Some recent studies have explored the possibility of increasing concurrently both timber production and ecosystem carbon stocks by changing the stand management (Briceño-Elizondo et al. 2006b, Garcia-Gonzalo et al. 2007a). Changing the current management may also be a solution to increase the share of energy biomass production at thinning and final felling together with timber production as was shown recently by Heikkilä et al. (2009). Those previous studies may mean that higher initial stand density and changes in thinning regime may produce more energy biomass at energy biomass thinning (energy wood thinning) and at final felling (logging residues) without reducing the timber production potential and carbon storage in the forest ecosystems.

Inclusion of energy biomass production, as an additional forest management objective, is reinforced mainly by the EU commitments to reduce its greenhouse gas emissions and increase the share of renewable energies to 20% by 2020 (EC 2008). Overall targets include reducing emissions, substituting fossil fuels with renewable energy and increasing the use of wood in construction (e.g. Eriksson et al. 2007). The target varies among the countries based on their historic use of renewable energy. For Finland, the target is to increase the share of renewable energy from 28.5% in 2005 to 38% by 2020. In this context, Finland aims to increase the share of renewable energy sources especially based on forest biomass. For example, Finland's 'National Forest Programme 2015' expects to increase the use of forest based energy biomass (wood chips) in energy generation from 3.4 million m^3 in 2006 to 8–12 million m^3 by 2015 (Finnish Ministry of Agriculture and Forestry 2008).

During the year 2006, total timber consumption in Finland was 81.5 million m^3, of which over 90% (about 76 million m^3) was used by forest industries (Peltola 2007). During the same year, the total amount of utilised energy biomass was about 21 million m^3, partly used in small-sized dwellings (6.1 million m^3) and in heating and power plants (14.8 million m^3). Of the total energy biomass, only 15% came from wood chips and the remainder, for example, combustion of bark, sawdust and industrial chips, were sourced from the sawmilling and plywood industries (Peltola 2007). Wood chips are, therefore, still a relatively modest source of fuel despite of its extensive growth potential (Hakkila 2004). A potential source of wood chips consists of branches and crown mass harvested from commercial thinnings and final felling, in addition to other tree components that do not fulfil the requirements for industrial use (e.g. low quality timber, stem tops, living and dead trees, and stumps and roots). Small-sized trees, harvested in energy biomass thinning, could also be used for energy generation (VTT 2001, Hakkila 2004).

Several previous studies have estimated the potential recovery of above and below ground energy biomass raw materials in Finland. Hakkila (2004) suggested that depending on the cost limit, the maximum technically harvestable energy biomass potential is 16 million m^3 a^{-1}, which is about 35% of the theoretical potential estimated from all above and below ground biomass residues of a hypothetical 70 million m^3 annual stem wood removal. In the study of Asikainen et al. (2008), the potential of annual logging residues was estimated to be in Finland about 24 million m^3, when considering stem wood loss, stem tops, branches and needles, stumps and roots as biomass components. Also Malinen et al. (2001) suggested that in southern Finland the economically feasible potential of energy biomass that could be harvested will be at maximum of 8.8 million m^3 a^{-1} over a 40-year period. In their study, energy biomass consisted of logging residues from final felling, branches, bark residues and stem wood from the first commercial thinning.

1.3 Sustainability in energy biomass production and utilisation

Large-scale harvesting of energy biomass will raise the question of how sustainable the energy systems based on biomass are and what are the climatic effects when forest biomass is used in energy generation? The use of energy biomass in lieu of fossil fuels has the advantage of carbon neutrality meaning that no additional carbon is released to the atmosphere if the forests are replanted to recapture the harvested carbon. However, the recovery of energy biomass needs fossil energy, thus, partly limiting the benefits of its use (Schlamadinger et al. 1995, Yoshioka et al. 2005). Moreover, from the forest management point of view, these emissions may vary depending on the utilised management operations (harvesting and transportation) and magnitude of management intensity (Eriksson et al. 2007). Recently, the carbon neutrality of energy biomass has also been questioned due to high indirect greenhouse gas emissions, which are related to land-use and land-use changes in producing bioenergy (Searchinger et al. 2008, Melillo et al. 2009). Regarding forest biomass, the indirect carbon emissions are also important when assessing the carbon sequestration in forest ecosystems and the role of forests in mitigating the climate change (e.g. Melin et al. 2010, Repo et al. 2010).

The utilisation potential of forest biomass is estimated according to the existing forest resources and different biomass components of trees (Hakkila 2004, Kärkkäinen et al. 2008, Heikkilä et al. 2009). These calculations do not, however, include the sink and source considerations of the whole forest production chain, although the identification of the biomass production alone is not enough when considering the capability and possibility of a forest ecosystem to mitigate the climate change. Despite this, there are still available only few whole ecosystem scale evaluations of environmental impacts of the use of forest biomass in energy production (Wihersaari 2005, Eriksson et al. 2007, Lindholm et al. 2010, Melin et al. 2010, Repo et al. 2010).

For this purpose, suitable tools are needed in order to evaluate the possibilities offered by the forests, forest management and forest based biomass in the mitigation of climate change and the substitution of fossil fuel in energy production. The holistic ecosystem level analysis of the carbon balance should include the aspects such as: i) the carbon uptake in tree growth, ii) the emissions caused by decomposition of soil organic matter controlling the sink/source dynamics of the ecosystem, and iii) the carbon emitted in management, harvesting and transportation as well. This is because all these phases in the production chain affect the carbon dynamics in the forest-atmosphere interactions and the potential of forest biomass in reducing the carbon emissions in energy production. Assessments are also needed over the whole life cycle of forest biomass production in order to identify the contribution of different factors on the sink/source dynamics of forest ecosystem and the role of forest biomass in mitigating the climate change.

Empirical growth and yield models are nowadays widely used to support decision making in practical forest management and forestry, when focusing on timber production (Peng et al. 2002, Zhou et al. 2005, Kangur et al. 2007). However, they have usually been parameterised based on past forest inventory data, and they assume that the climatic conditions and the forest management are not changing in the future compared to the past. As a comparison, the use of ecosystem models (i.e. process-based models) has been limited so far in decision making of practical forestry because they require more complex parameterization and input datasets which are not typically provided by conventional forest inventories. On the other hand, they can provide the same prediction capacity as empirical models for practical management situations under the current climate (see e.g. Peng et al. 2002, Matala et al. 2003, Zhou et al. 2005). Furthermore, unlike empirical models, they can also provide predictions of forest growth under the changing climatic and management conditions, as they link the growth and development of tree stands with climatic and edaphic factors (directly and indirectly). Similarly, life cycle assessment (LCA) tools as integrated with ecosystem model simulations could make it possible to analyse carbon exchange of and sustainability of forest production in the context of the climate change mitigation.

1.4 Aims of the study

The main aim of this study was to investigate the effects of forest management and climate change on energy biomass and timber production with implications for carbon stocks and net CO_2 exchange in boreal forest ecosystems in Finnish conditions (See Figure 1). Specific research tasks of the study were as follows:

I. To investigate the impacts of thinning on growth, timber production and carbon stocks under current and changing climate for Finland (Article I).

II. To investigate the potential energy biomass production with implications for timber production and carbon stocks under varying thinning regimes and climate scenarios for Finland (Article II).

III. To develop a LCA tool for estimating net CO_2 exchange of forest production in boreal forest ecosystems (Article III).

IV. To investigate the impacts of varying initial stand density and thinning regimes on energy biomass production and management related CO_2 emissions in Finnish boreal forest ecosystems (Article IV).

2 MATERIAL AND METHODS

2.1 General outlines

The analysis in this study followed the schematic approach shown in Figure 1. The growth and development of forests was simulated by utilising an ecosystem model (Sima), which provides prediction on growth (m^3 ha^{-1} a^{-1}), energy biomass (Mg ha^{-1} a^{-1}) and timber (m^3 ha^{-1} a^{-1}) production, as well as carbon stocks (Mg ha^{-1}) in the forest ecosystem (Articles I–IV). The timber was sorted into sawlogs and pulpwood, with a minimum top diameter of 15 and 6 cm, respectively. Other parts of trees, e.g. branches, tops of the stem, needles (harvesting loss was assumed about 30%), stumps and large roots, were logging residues. Harvested energy biomass included logging residues only at final felling and small-sized trees at energy biomass thinning. The carbon stocks referred to the carbon in stems, branches, leaves and roots in the growing stock (standing trees) and in the ground vegetation and forest floor (decaying biomass, litter and humus), and standing dead trees. The calculations utilised wood density of 400 kg m^{-3}, while the carbon content in dry biomass was 50%.

Analysis focused mainly on either the effects of the changing climate and/or that of thinning regime on growth, energy biomass and timber production, and carbon stocks in the forest ecosystem (Articles I–IV). In addition, controlled simulations were done to separate the effects of changing climate and forest structure (age class distribution) on forest growth during the whole simulation period (Article II). In these simulations, the initial forest structure was kept the same regardless of the stage of the simulation period (three 30-year periods) and the forest dynamics were simulated until the end of each 30-year period both under the current and changing climate.

The resulting energy biomass and timber production from the simulations were subsequently utilised as inputs for the LCA tool developed in this work (Article III) for estimating CO_2 exchange of forest production and fossil fuel emissions per unit of energy biomass production (Articles III & IV). Emissions were partitioned into energy biomass and timber according to their biomass recovery in thinning and final felling over the rotation period. However, all the emissions of stand establishment were included, as such, in the emissions calculation. The utilised model outputs include carbon uptake into forest biomass, and emissions of carbon from management operations, from soil litter and humus decomposition and from degradation of timber products and energy biomass combustion.

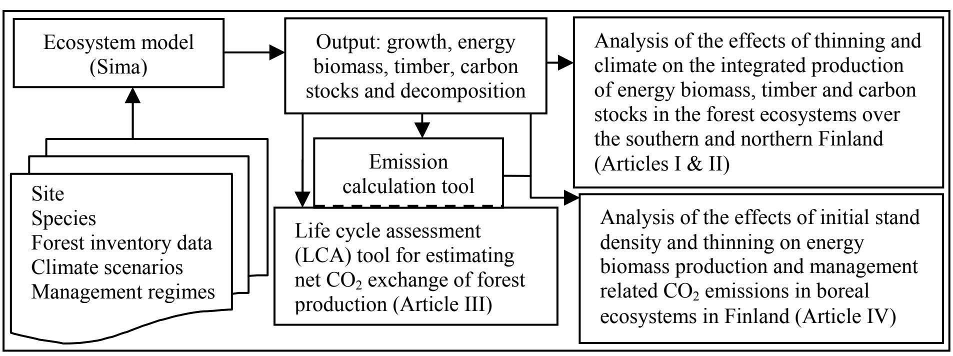


Figure 1. Outline of this study.

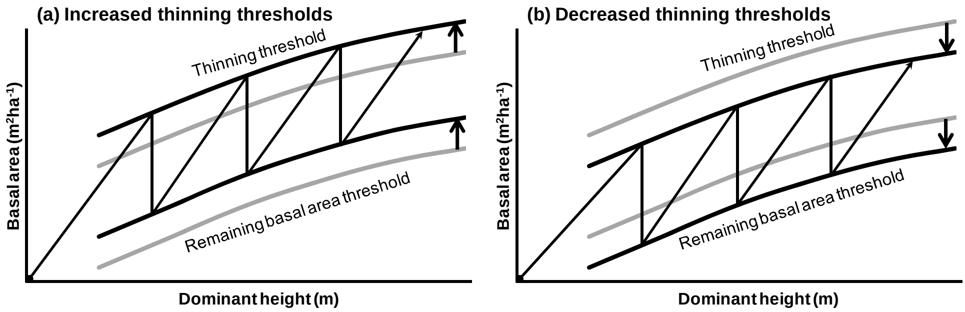
In Articles I & II, the simulations were run for the whole of southern and northern Finland, for all the main tree species growing in the country under the current and changing climate. Data from the Finnish National Forest Inventory (NFI) were used as a model input in Article I (NFI8) and Article II (NFI9). Whereas in Articles III & IV, seedlings with 2 cm diameter were used as inputs for initial stand data in the simulations. In Article III, stand level simulations were done for Norway spruce (*Myrtillus*, MT site) both in southern (Joensuu region: 62˚40΄N, 29˚30΄E) and northern Finland (Rovaniemi region: 66˚34΄N, 25˚50΄E) under the current and changing climate. In Article IV, the simulations at stand level were done for Scots pine (*Vaccinium*, VT and MT sites) and Norway spruce (MT and *Oxalis-Myrstillus*, OMT sites) growing in southern Finland (Joensuu region) only under the current climate. In this work, OMT, MT and VT represent the most fertile, medium fertile and less fertile sites, respectively.

2.2 Management regimes and climate scenarios

In the simulations, energy biomass thinning (EBT), commercial thinning, final felling and regeneration were used as management operations. The thinning rules, based on the development of basal area and dominant height, followed those currently recommended for different tree species, site fertility types and regions in Finland (Yrjölä 2002, Tapio 2006). 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. EBT was also done based on site and species specific recommendations for the dominant stand height and basal area, and remaining stand density (Tapio 2006). The final felling 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 (Articles I & II) or a fixed rotation length of 80 years (Articles III & IV).

The modified management regimes were constructed by means of changing both the basal area thresholds, when the thinning was performed and the remaining basal area after the thinning (see Figure 2) (Articles I–II & IV). In addition, varying initial stand density, from 2000 to 4000 seedlings ha^{-1}, was used in the stand level analysis (Article IV). With the exception of timber production regime (TP) (Articles III & IV), where only timber was produced, all the other management regimes included energy biomass production in EBT and final felling. The thresholds for EBT were always similar for both current and increased thinning thresholds. With decreased thinning thresholds, the species-specific stand density was reduced, though it was kept within the recommendation of Tapio (2006).

The simulations utilised the current climate (Articles I–IV) and changing climate scenarios (Articles I–III), provided by the Finnish Meteorological Institute (Ruosteenoja et al. 2005, Ruosteenoja and Jylhä 2007, Jylhä et al. 2009). The changing climate was based on the A2 scenario (IPCC 2007) and given in three 30-year periods i.e. near-term, mid-term and long-term. In Article I, an older climate scenario was utilised (1990–2020; 2021–2050; 2070–2099), for which, by 2100, temperature increased almost 4°C in the summer and 6°C in the winter and precipitation increased more than 20% in the winter time. In the summer, it remained nearly unchanged (Ruosteenoja et al. 2005). The updated climate scenario (2010–2039; 2040–2069; 2070–2099) (Ruosteenoja and Jylhä 2007, Jylhä et al. 2009), utilised in Articles II & III, differed slightly compared to the previous one. In this latter scenario, summer time temperature was slightly lower and precipitation was slightly higher in the last period (2070–2099), on average, over the whole Finland. The opposite was the case for winter time. However, the average annual increases in temperature, compared to



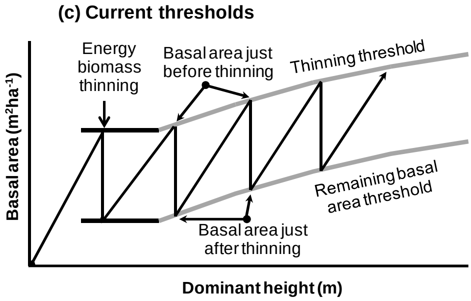


Figure 2. Principles of the thinning regimes applied in this study. Energy biomass thinning (EBT) was done for both current and changed thinning regimes depending on dominant tree height and basal area, and remaining stand density. Regular thinning was done based on the development of basal area and dominant height and current recommendation was considered as current thinning regime (c). Current thinning indicated by grey lines were changed by increasing (a) and decreasing (b) the thresholds.

the current climate, were quite similar for both climate scenarios. Similarly, the CO_2 concentration, in both changing climate scenarios, was estimated to rise from the current (1990) 367 to 840 ppm by 2100. The uncertainty regarding the level of the climate change was higher for the long-term projection period compared to the near- and mid-term periods. This is partly based on the large uncertainties in the predictions due to the increased levels of global greenhouse gas emissions for different scenarios. Therefore, they can be considered more as an example of probable climatic conditions at the end of this century.

The grid for the climate data originally represented 10 km × 10 km for the current climate and 50 km × 50 km for the changing climate. The model applied it in a 50 km × 50 km grid for both the current and changing climate. However, the effects of upscaling the grid size were assumed to be minor as most of the land areas in Finland are comparatively flat. Based on the available climate data, the monthly mean temperature and monthly mean precipitation (both with standard deviation) were calculated over the periods applied in the Sima model. In the case of the climate change scenarios, the monthly mean temperature and precipitation represented the mid-point of the period used in the model. The values between the mid-points were 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 for the closest grid point of the climate data.

2.3 Outlines of ecosystem model (Sima)

In the Sima model (Kellomäki et al. 1992a,b, Kellomäki and Kolström 1994, Talkkari and Hypén 1996, Kolström 1998, Kellomäki et al. 2008), the dynamics of the forest ecosystem are assumed to be determined by the dynamics of the number and mass of trees as regulated by their regeneration, growth and death. All these processes are related to the availability of resources, which in turn are regulated by the dynamics of the gaps in the canopy of the tree stand. The model is run on an annual basis and the computations are applied to an area of 100 m^2. The model is parameterised for Scots pine, Norway spruce, silver birch, downy birch, aspen (*Populus tremula* L.) and grey alder (*Alnus incana* Moench., Willd.) growing between the latitudes N 60° and N 70° and longitudes E 20° and E 32° within Finland.

The model utilises four environmental subroutines (temperature, light, moisture and nitrogen) describing the site conditions that affect growth and development of forests. Temperature controls the geographical thresholds and annual growth response of each species and their ecotypes. Simultaneously, competition for light controls tree growth and is dependent on tree species and their height distributions. The effect of soil moisture is described through the number of dry days, i.e. the number of days per growing season with soil moisture equal or less than that of the wilting point specific for soil types and tree species. Soil moisture indicates the balance between precipitation, evaporation and runoff (Kellomäki et al. 1992a,b, 2008). The availability of nitrogen is controlled by the decomposition of litter (amount of dead materials originating from trees and ground vegetation e.g. foliage, twigs, roots, stems of standing and fallen dead trees) and soil organic matter (humus), which is dependent on the quality of litter (nitrogen and lignin content), humus and evapotranspiration. The decomposition of litter and humus is treated as cohorts and is determined based on the weight loss, nitrogen immobilisation and mineralisation, lignin decay and CO_2 loss. The total available nitrogen for the trees and the ground vegetation is the difference between the total mineralised nitrogen and the immobilised nitrogen in decomposition (Kellomäki et al. 1992a,b, 2008).

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_o 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. In addition, in the case of growth, the values of G_o 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_o calculation are based on the simulations of a physiological growth and yield model applying the same methodology as Matala et al. (2005). 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 no shading in the Finnish conditions.

The simulation of the above forest ecosystem processes is based on the Monte Carlo simulation technique. That means certain events, such as the death of trees, are stochastic. Whenever such a possibility occurs, the algorithm selects whether or not the event will take place by comparing a random number with the probability of the occurrence of the event. The probability of an event occurring is a function of the state of the forest ecosystem at the time when it is possible. Each run of a Monte Carlo code is one realisation of all possible time courses of the development of the forest ecosystem. Therefore, the simulation needs to be repeated several times in order to determine the convergence of the model.

2.4 Life cycle assessment (LCA) tool

The LCA tool developed in this work (Article III) calculates the net CO_2 exchange (C_{net}) of forest production on an annual basis (g CO_2 m^2 a^{-1}) as indicated by Equation (1). It includes components both from the ecosystem and from the technosystem related to the forest production within the system boundary (Figure 2, Article III). C_{net} is a sum of the carbon uptake in growth (C_{seq}) and carbon emissions. The emissions consist of carbon from management and the harvest (C_{man}), decomposition of soil organic matter (C_{decomp}) and combustion of energy biomass and degradation of wood-based items manufactured from timber (C_{harv}). In calculations, C_{seq} has negative values (carbon is flowing from atmosphere to forest), while the emissions C_{man}, C_{decomp} and C_{harv} have positive values (carbon is flowing from forests, energy biomass and wood-based items to atmosphere).

$$C_{\mathrm{net}} = C_{\mathrm{seq}} + C_{\mathrm{man}} + C_{\mathrm{decomp}} + C_{\mathrm{harv}} \quad (1)$$

In the calculations, all the main phases of forest production (energy biomass and timber) with relevant operations were included (Article III & IV). Thus, the life cycle of energy biomass and timber starts from seedling production in the nursery and proceeds through management and harvesting and ends up at the yard of a pulp mill (pulpwood), sawmill (sawlogs) or power plant (energy biomass) (Figure 2, Article III). The carbon emitted in management, harvesting and logistical operations during the life cycle was included in the calculations through consumption of fuel (diesel) or electricity. The parameters for productivity of operations and fuel consumption of machines, with corresponding units and references, were collected from the available literature (Table 2, Article III).

The values for container seedlings were used to define the values for seedling production. Site preparation was assumed to be done with an excavator or scarifier. The parameter values for logging (cut-to-length method) and forest haulage were for a harvester and forwarder with different values for thinning and final felling. The values for the transportation of machines (e.g. harvester, scarifier) from site to site were based either on productivity per area or per solid m^3. Long distance transportation of energy biomass and timber was assumed to be done with a truck. The return journey for the truck (empty) was assumed to consume 70% of the fuel needed for a full load. In the case of energy biomass, chipping was assumed to be done at the yard of the power plant with a large-scale drum chipper. In addition, commuter traffic in various phases of production was included in the calculation by assuming working hours and travel using a personal car. The manufacturing and maintenance of working machines were excluded from the calculation.

Timber (pulpwood and sawlogs) was converted into usable wood-based products, and the carbon emissions from the items no longer in use were calculated applying Equation (2) (Karjalainen et al. 1994).

$$PU = d - \frac{a}{1+be^{-ct}} \quad (2)$$

where PU is the proportion (0…100) of products in use; a (120), b (5), d (120) are fixed parameters; c ($year^{-1}$) is lifespan of a product (0.15 for medium-short and 0.065 for medium-long) and t (year) is time. In this work, pulpwood represented the items with a medium-short lifespan, while the sawlogs, items with medium-long lifespan. The carbon released from products no longer in use was assumed to convert completely into CO_2.

The allocation of carbon emissions (or uptake) for energy biomass (MWh^{-1}) and timber (m^{-3}) was done from the net carbon exchange and according to the produced biomass proportions over the rotation. C_{harv} of energy biomass (combustion) was not allocated for timber and vice versa. The management related emissions were also allocated according to the produced biomass proportions of energy biomass and timber over the rotation.

3 RESULTS

3.1 Ecosystem model based analysis of the effects of thinning and climate on growth, energy biomass and timber production, and carbon stocks (Articles I & II)

Growth, timber production and carbon stocks (Articles I & II)

In general, the climate change increased forest growth, timber production and carbon stocks in the forest ecosystem in both southern and northern Finland in all three periods. The relative changes were similar for all the thinning regimes, but they varied between the regions, being higher in northern Finland (Articles I & II).

In Article I (for all the periods), for both southern and northern Finland, increased basal area thinning thresholds (up to 30%) compared to the current thinning regime, reduced timber production under changing climate but did not greatly affect growth or carbon stocks under the current or changing climate. Conversely, both in southern and northern Finland, decreased basal area thinning thresholds compared to current thinning, increased timber production, which exceeded annual growth regardless of the period. In addition, decreased basal area thresholds reduced carbon stocks in the forest ecosystem in both regions compared to that with current thresholds (Tables 2–4, Article I).

In Article II, during the first period (2010–2039), under current and changing climate, increased basal area thinning thresholds enhanced growth, compared to the current thinning regime in both southern and northern Finland (Figure 6, Article II). During the same period, increased thinning thresholds, compared to current thinning increased carbon stocks in the forest ecosystem, but reduced timber production for both current and changing climate in southern and northern Finland (Figure 6, Article II). In both southern and northern Finland, during the second period (2040–2069), growth, timber production and carbon stocks increased with increased thinning thresholds in both the current climate and the changing climate. During the final period (2070–2099), increased thinning thresholds enhanced growth and carbon stocks regardless of region and climate scenario, but timber production increased only under the changing climate in northern Finland (Figure 6, Article II).

Energy biomass production (Article II)

In general, the energy biomass production (small-sized trees) from energy biomass thinning (EBT) increased over time both for current and changing climatic conditions in southern as well as in northern Finland. During the first period (2010–2039), in southern and northern Finland, neither increased basal area thinning thresholds, compared to current thinning regime, nor the changing climate, affected the energy biomass production at EBT. During the second period (2040–2069), increased basal area thresholds did not affect the energy biomass production at EBT, neither in southern nor in northern Finland. However, the changing climate increased energy biomass production at EBT in both regions. During the final period (2070–2099), in both southern and northern Finland, the changing climate increased the energy biomass production at EBT. Conversely, increased basal area thresholds increased the energy biomass production at EBT only under the changing climate (Figure 5, Article II).

The energy biomass production (logging residues) at final felling was higher during the second period (2040–2069) compared to the first (2010–2039) under both current and changing climate in southern as well as in northern Finland, but it was highest during the third period (2070–2099) under changing climate in southern Finland. During the first period (2010–2039), in both regions, increased basal area thinning thresholds, compared to the current thinning regime did not affect the energy biomass production at final felling under current or changing climate, but the climate change increased the production at final felling. During the second (2040–2069) and final period (2070–2099), both climate and increased thinning thresholds enhanced the energy biomass production at final felling both in southern and northern Finland (Figure 5, Article II).

Separated effects of climate and forest structure on forest growth (Article II)

According to the additional (controlled) simulations, the effects of forest structure on forest growth, in relative terms, were more pronounced than that of changing climate (Figure 7, Article II). The effects of changing climate on forest growth were found to be higher in the north than in the south. On the other hand, the effects of forest structure were higher in the south than in the north under both current and changing climate. In addition, there was no forest structure effect found during the first period.

3.2 Integration of ecosystem modelling and LCA tool for analysing the effects of management and climate on CO_2 exchange of forest production (Articles III & IV)

Computational example of CO_2 exchange of forest production (Article III)

In the stand level calculations, the ecosystem model simulations produced the annual growth (stem, branches, foliage, coarse roots and fine roots) (C_{seq}), and the amount of biomass harvested (C_{harv}) in EBT, in the commercial thinnings (timber) and in the final felling (energy biomass, timber). Moreover, the model produced the annual litter fall for the decomposition and consequent emissions of carbon from soil (C_{decomp}) to be used in the LCA tool, including carbon emissions from harvested energy biomass combustion and timber degradation. The example simulations were done only for a Norway spruce stand for traditional timber production (TP) and for the integrated energy biomass and timber production (BP) regime under the current and changing climate during a rotation length of 80 years. In general, the changing climatic conditions increased decomposition for both the TP and BP regimes in southern as well as northern Finland (Table 2, Article III). In southern Finland, CO_2 uptake (C_{seq}) and net CO_2 exchange (C_{net}) values increased under the changing climate for both TP and BP regimes. In northern Finland, the situation was opposite both in TP and BP regime. Regardless of climate scenario, the BP regime had higher C_{net} values compared to the TP regime for both southern and northern Finland, as expected due to combustion related emissions in BP regime (Table 2, Article III). In both southern and northern Finland, regardless of climate and management, the share of emissions from decomposition (C_{decomp}) were highest (69–90%), followed by energy biomass combustion (C_{harv}, energy biomass) (21–26%) and timber degradation (C_{harv}, pulpwood and sawlogs) (1–9%). Management operations (C_{man}) emitted the least, estimated to be about 1% compared to the whole emissions chain over the 80-year rotation period (Table 2, Article III).

In the simulation, the decomposition was divided into new (litter fall build up during the rotation) and old (prevailing at the beginning of the simulation) humus. Neither management nor climate was sensitive to the decomposition of the old humus unlike that of new humus both in southern and northern Finland. However, the changing climatic conditions, compared to the current climate increased and BP regime, compared to TP, decreased the decomposition of new humus in the Norway spruce stand, both in southern and northern Finland (Figure 5, Article III).

In the calculation of the emissions allocated for energy biomass and timber (pulpwood and sawlogs), pulpwood and sawlogs were found to net sequestrate carbon during the calculated rotation period for both southern and northern Finland (Table 3, Article III). Only in northern Finland, pulpwood produced in BP under changing climate had a net loss of carbon. In both southern and northern Finland, the highest amount of sequestered carbon was found in sawlogs regardless of management regime, though it should be noted that in northern Finland in BP no sawlogs were produced under the current climate. However, the changing climatic conditions increased the emissions for energy biomass production in southern Finland, though they reduced it in northern Finland, for the BP regime (Table 3, Article III).

The effects of initial stand density and thinning regimes on energy biomass production and related CO_2 emissions (Article IV)

The effects of varying initial stand density and thinning regimes on total energy biomass production (small-sized trees and logging residues) and emissions per energy unit of produced energy biomass (kg CO_2 MWh^{-1}) were analysed over the 80-year rotation period for Scots pine stands growing on MT and VT sites and Norway spruce stands growing on OMT and MT sites in southern Finland (Joensuu region) (Figures 8 and 9, Article IV). The results showed that the energy biomass production of the Norway spruce stands was higher than that of the Scots pine stands. However, the emissions per energy unit of energy biomass production were lower for Norway spruce compared to Scots pine. It was also found, for both species, that energy biomass production was higher in the more fertile sites and also sites with higher initial stand density, regardless of thinning regimes.

For Scots pine with initial stand density of 2000–4000 seedlings ha^{-1}, increased basal area thinning thresholds, compared to current baseline thinning, increased energy biomass production and decreased CO_2 emissions at the MT site (Figure 8, Article IV). However, the opposite results were found for decreased thinning thresholds for the same species at both MT and VT sites. At the VT site, the increased thinning thresholds had a similar pattern to the MT site regarding energy biomass production and CO_2 emissions, except for initial stand density of 2000 seedlings ha^{-1} for which energy biomass production was reduced slightly when increased thinning thresholds were compared to the current thinning regime.

For Norway spruce growing on the OMT and MT sites, decreased thinning thresholds, compared to current thinning thresholds, affected energy biomass production and management related CO_2 emissions in a similar way as to Scots pine i.e. reduced energy biomass production and increased emissions per energy unit of energy biomass production (Figure 9, Article IV). The only exception was found at the OMT site with initial stand density of 2000 seedlings ha^{-1} where both energy biomass and CO_2 emissions values were lower. However, up to a 20% increase in basal area thinning thresholds, compared to current thinning did not show any major changes in energy biomass production and management related CO_2 emissions. A 30% increase of these thresholds increased the energy biomass production and reduced CO_2 emissions for both OMT and MT sites, regardless of initial stand density.

4 DISCUSSION AND CONCLUSIONS

4.1 Evaluation of the modelling approaches

In this work, a gap type ecosystem model (Sima) (Kellomäki et al. 1992a,b) was used to study the effects of thinning and climate on the integrated production of energy biomass and timber, and carbon stocks in the forest ecosystem in Finnish boreal conditions (Articles I–IV). In addition, management related CO_2 emissions and net CO_2 exchange for forest production were assessed under varying management regimes (initial stand density and/or thinning regimes) with the developed LCA tool (Articles III & IV).

Estimation of the net atmospheric impact of forest production in an ecosystem includes flows of carbon in the whole system. In this study, above- and below-ground carbon uptake of trees (forest growth) and decomposition of humus and litter was simulated by using the Sima model. The model has earlier produced a close correlation between measured and simulated stem volume growth of different tree species for Finnish conditions based on NFI data (Kellomäki et al. 2005, 2008, Routa et al. 2010). The Sima model is expected to be capable of predicting the development of the boreal forest ecosystem also under changing climatic conditions in a reasonable way (Kellomäki et al. 2005, 2008). This is because the model is able to calculate the growth response of trees to changing climatic conditions, including the elevation of temperature and atmospheric CO_2 concentration, and changes in precipitation (see Kellomäki et al. 2008). However, the growth predictions for the future are also dependent on the uncertainties of the changing climate scenarios. The accuracy of prediction of the changing climate decreases especially in the long-term period, which is discussed in great detail by, for example, Ruosteenoja et al. (2005) and Jylhä et al. (2009). However, the use of the site-specific climatic data for the closest grid may improve the growth predictions. On the other hand, it should be noted that in the model simulations the effects of forest damages (e.g. wind throw, insect attack and forest fire) are not considered on forest growth and development, though random mortality is included in simulations.

The outputs of the ecosystem model, as integrated with emissions parameter values attained from the available literature, were linked to the LCA tool developed in this work. This enabled the assessment of all the significant carbon fluxes and carbon emissions related to the forest production and management in forest ecosystems within the set system boundaries (Article III). The approach was found to be useful to assess the net carbon exchange and its interactive effects on biomass and litter production, management operations, changed climatic conditions and soil processes on an annual basis or for a longer time period. In this way, the atmospheric impacts of energy biomass production and utilisation could be investigated for alternative forest management regimes and climate scenarios as shown in the results. The approach also enabled the estimation of both direct and indirect emissions through alternative scenarios and, more importantly, emission dynamics related to ecosystem processes affected by management and changing climatic conditions. The selection of system boundary, in addition to the temporal aspects of the forest biomass production and utilisation, are among the key factors for estimating carbon flows to and from the atmosphere. Changes to them may affect the LCA results considerably. In this work, a fixed time period was chosen for the analyses (Articles III & IV), since the aim was to demonstrate the performance of the LCA tool in terms of sink/source dynamics and to compare CO_2 exchange of the management regimes and climate scenarios applied.

4.2 Evaluation of the simulation results

The results showed that under the changing climate, stem volume growth increased substantially in both southern and northern Finland, with the relative increase being similar for all the thinning regimes applied. The largest relative changes were found in northern Finland, though the absolute values were higher in southern Finland. Other studies have also found a corresponding growth increase under the changing climate (elevated temperature and CO_2 concentration) (Kellomäki et al. 2005, Kilpeläinen et al. 2005, Briceño-Elizondo et al. 2006a). Currently, temperature is limiting tree growth in northern Finland (Kellomäki et al. 2005) and an increase in it will enhance tree growth in the future. This is also partly the case for southern Finland, but drought periods in summer time will limit tree growth there more than the lack of warm temperatures. The reduced growth is most probable for Norway spruce on sites with low water holding capacity (Lasch et al. 2002, Kellomäki et al. 2005, 2008), which was also found in this study. On the other hand, elevated CO_2 concentrations have been found to increase the water use efficiency of trees (Thornley and Cannell 1996) and compensate, at least to some degree, for the growth reduction, as previous studies show (Kellomäki and Väisänen 1997, Briceño-Elizondo et al. 2006a).

Apart from the changing climate, forest growth may also be affected by the prevailing forest structure (Garcia-Gonzalo et al. 2007b). In this study, the relative effect of forest structure on growth was found to be larger than that of climate (Article II). The effect was higher in southern than in northern Finland, opposite to the effect of the climate. Garcia-Gonzalo et al. (2007b) reported that the 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 for different management regimes. This is a result of the differences in management interventions applied (e.g. thinning and timing of final felling) over the simulation period, affecting forest structure and composition of forest ecosystems (Garcia-Gonzalo et al. 2007b, McDonald et al. 2008, Russell 2009).

Thinnings are well known to influence forest production potential. This study utilised basal area and dominant height based thinning system, which lead to the number of thinnings varying among the regimes. The removal of basal area (thinning intensity) was, in this system, determined by the changes in thinning thresholds from the reference point (current practice). Increased thinning thresholds maintained higher tree stocking after thinning, which decreased the radial growth of individual trees. The increase in thinning thresholds resulted in a delay in successive thinnings. Conversely, decreased thinning thresholds increased the number of thinnings over the rotation compared to the current thresholds, and enabled single tree to grow faster due to reduced competition of growth resources (Article IV). This was the case especially during the early phase of the stand development and was partly affected by the EBT. As a result, each thinning had less harvestable timber as was also found elsewhere (Thornley and Cannell 2000, Mäkinen and Isomäki 2004a,b, Briceño-Elizondo et al. 2006a).

In order to increase energy biomass production integrated with timber production, an increase of initial stand density from the conventional practice of 2000 seedlings ha^{-1} has been suggested in previous studies (Heikkilä et al. 2009). Also in this study, increasing the initial stand density was found to enhance energy biomass production at EBT, however, at some sites, energy biomass production at final felling was reduced. This was the case, for example, for Scots pine on VT and for Norway spruce on OMT sites (Article IV). This was mainly caused by the fact that increased initial stand density made EBT occur earlier and therefore, subsequent thinnings were delayed, compared to initial stand density of 2000 seedlings ha^{-1}. Because of the delayed thinning, the time interval between last thinning and final felling was shortened and thus, optimal growth potential remained unutilised during the later stages of the rotation period. A similar trend also held when both initial stand density and thinning thresholds were increased. This affected not only the energy biomass production at final felling but also timber production and ecosystem carbon storage.

However, the concurrent analyses of energy biomass, timber and carbon stocks showed that a concurrent increase in them was possible during the second period (2040–2069) if thinning thresholds were increased from the current recommendation (Article II). In the case of timber and carbon, this is in agreement with the findings of Thornley and Cannell (2000), Briceño-Elizondo et al. (2006a,b) and Garcia-Gonzalo et al. (2007a,b). They concluded that management with higher tree stocking and fewer disturbances throughout the rotation could maximise production of both timber and carbon stocks. Increased timber production could also increase the energy biomass production as reported by Maclaren (2000). However, Seely et al. (2002) suggested a trade-off between ecosystem carbon storage capacity and timber production since these two represent competing demands. This was found also in this study during the first (2010–2039) and final periods (2070–2099) of Article II and all the three periods in Article I.

In this study, the estimated potential of energy biomass production at final felling was ca. 6.6 Tg a^{-1} (16 million m^3 a^{-1} or 40 TWh a^{-1}) for the whole of Finland (Article II). These calculated values were lower compared to those estimated by Hakkila (2004), Asikainen et al. (2008) and Kärkkäinen et al. (2008). This might be due to the differences in cutting scenarios, logging residues components and their recovery at varying thinning stages, limiting the comparability of different studies. However, the estimations in this study are partly affected by practical limitations. The results should, thus, be considered as theoretical potentials. In Finland, harvesting of energy biomass has not been so far as extensive as its potential (Malinen et al. 2001, Hakkila 2004). The utilisation of energy biomass is useful when it is a substitute for coal and oil. However, it has also negative effects as the removal of organic matter, and thereby nutrients, could affect the future forest growth (Jacobson et al. 2000, Palviainen et al. 2009). In Finland, the harvesting of logging residues are recommended at comparatively higher productive sites and 30% of the removals should be left at the site thereby ensuring the nutrient availability (Äijälä et al. 2010). This suggestion is in line with the recovery that has been applied in this study.

From the mitigation and substitution view point, investigating production potentials and utilisation possibility of energy biomass alone is not enough since their recovery consumes energy and releases carbon to the atmosphere. However, management related emissions are low compared to total ecosystem exchange, with decomposition of soil organic matter being the main sources of indirect emissions (Repo et al. 2010). It is generally assumed that the decomposition process will be accelerated by warmer climate (Davidson and Janssens 2006, Karhu et al. 2010). If increased decomposition exceeds plant derived carbon input to the soil, the carbon flows to the atmosphere will increase (Johnson and Curtis 2001, Ågren and Hyvönen 2003, Eriksson et al. 2007, Crow et al. 2009), which further increases the climatic impacts of energy biomass use. Management has substantial effects on the uptake and emissions of carbon and thus the appropriate choice of the management regime is among the key questions in mitigating the climate change in biomass production. The temporal dimension is also crucial due to the dynamic nature of the forest ecosystem for its subsequent effect on the emissions allocation and prevailing carbon stocks at the end of the calculation period (Schlamadinger and Marland 1996, Melin et al. 2010, Repo et al. 2010).

However, understanding the potential of forest ecosystems and forest biomass utilisation for the climate change mitigation requires all the production related issues to be integrated in order to assess the net atmospheric impacts on forest production. In this context, the LCA tool developed in this work allows the estimation of the net carbon exchange of the forest production in boreal conditions (Article III).

When applying the LCA tool in interaction with ecosystem model simulations, it was found, in this study, that increased thinning thresholds compared to current thinning, enhanced energy biomass production and reduced management related CO_2 emissions (Article IV). The emissions per unit of produced energy for Norway spruce were lower than that for Scots pine, which can be expected as a result of the higher crown mass in Norway spruce compared to Scots pine (Hakkila 1991, Röser et al. 2008). The management related emissions for the energy biomass production were 7.7–10.5 kg CO_2 MWh^{-1} depending on the management regime (Article IV), in the range (4–20 kg CO_2 MWh^{-1}) reported by other studies (Börjesson 1996, Mälkki and Virtanen 2003, Wihersaari 2005). However, the main part of the carbon emissions per energy unit originated from the decomposition of soil organic matter and from the combustion of biomass (Article III). The calculated value for the net carbon exchange were found to be in the range of -49 to -337 g CO_2 m^{-2} and emissions allocated for the energy biomass were 157–199 kg CO_2 MWh^{-1} for a Norway spruce stand depending on management regimes, climatic conditions and regions of Finland (Article III).

4.3 Conclusions

In summary, 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 for energy biomass production, integrated with timber production and carbon storage, in the context of the climate change mitigation. In the future, the climate change may require the current forest management to be adapted in order to utilise the higher growth rate and thus, increased carbon sequestration and production potential of the forest ecosystems in boreal conditions. On the other hand, a warmer climate could also increase carbon loss from the ecosystem through decomposition. Thus, this could partly limit the climate change benefits in the context of ecosystem carbon exchange and fossil fuel replacement by energy biomass. In this work, it was found that it is possible to simultaneously increase the growth and energy biomass and timber production as well as carbon stocks in the forest ecosystem by changing the forest management in terms of increased thinning threshold and initial stand density. Changed management could also decrease CO_2 emissions for energy biomass production. Understanding the potential offered by forests in the context of the climate change mitigation also requires consideration of the emissions of carbon from soil decomposition processes in the analysis. The combined use of ecosystem model simulations and the LCA tool provides an appropriate means to analyse carbon exchange of forest production and sustainability of forestry in this respect. Future studies are needed in order to evaluate more in details in which scale the energy biomass potential could be used to substitute fossil fuels maintaining sustainability of the forest ecosystems.

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