**Dissertationes Forestales 123**

# Effects of forest management on sustainability of integrated timber and energy wood production - scenario analysis based on ecosystem model simulations

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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 criticism in Metla-talo Auditorium Käpy, Yliopistokatu 6, Joensuu, on 10th June 2011, at 12 o'clock noon.

*Title of dissertation*: Effects of forest management on sustainability of integrated timber and energy wood production - scenario analysis based on ecosystem model simulations

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*Dissertationes Forestales 123*

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ISSN 1795-7389
ISBN 978-951-651-336-5 (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

**Routa, J.** 2011. Effects of forest management on sustainability of integrated timber and energy wood production - scenario analysis based on ecosystem model simulations. Dissertationes Forestales 123. 31 p.
Available at: http://www.metla.fi/dissertationes/df123.htm.

**ABSTRACT**

The main aim of this thesis was to study the effects of forest management on the sustainability of integrated timber and energy wood production in Norway spruce (*Picea abies* (L.) Karst.), on fertile and medium fertile sites, and Scots pine (*Pinus sylvestris* L.), on medium fertile and less fertile sites. In this context, an ecosystem model was used in scenario analyses, which considered the effects of management on the total stem wood production, timber and energy wood production. Furthermore, the management implications for net present value (NPV) and net $CO_2$ emissions of the use of energy wood was addressed. The management included varying pre-commercial stand density, timing, and intensity of energy wood thinning, N fertilization (Papers II-IV), and rotation length (Paper IV). In addition, the effects of the genetic entry on above-ground biomass production of Norway spruce were studied based on experimental data (Paper I).

In general, the management with higher pre-commercial stand density than that used in basic management and N fertilization clearly increased stem wood production (i.e. sawlogs, pulp and small-sized stem wood), energy wood production (logging residuals, small-sized stem wood, stump wood and roots) and also NPV over the rotation for both Norway spruce and Scots pine, regardless of site fertility type and rotation length used in the simulations (Papers II-IV). However, the total stem wood production and energy wood production were also affected by the timing of energy wood thinning. Fertilization had a positive effect, but the effects of number of applications and amount of N fertilization were negligible on the total stem wood and energy wood production. Additionally, in the case of net $CO_2$ emissions, the increase of pre-commercial stand density and fertilization clearly decreased the net $CO_2$ emission in energy production over the rotation regardless of tree species, site fertility type and rotation length used in simulations (Papers III-IV). In general, high stem wood production indicated concurrently, on average, higher NPV and lower $CO_2$ emissions per energy unit regardless of tree species and site fertility type.

At the landscape level, the highest amount of timber and energy wood and the NPV was obtained in Norway spruce on landscape dominated by older stands (Paper IV). The lowest net $CO_2$ emissions were obtained with the landscape dominated by younger stands with rotation length of 60 and 80 years, regardless of site fertility type. The same was observed with the normal age-class distribution with rotation length of 120 years. The use of higher density of pre-commercial stand than that currently recommended in Finnish forestry together with timely thinning and fertilization could increase the stem wood production and the economic profitability of the management remarkably, but also simultaneously decrease the net $CO_2$ emissions from the use of energy wood. Furthermore, the proper selection of genetic entries could increase also the productivity and potential of biomass recovery at least in Norway spruce (Paper I).

**Keywords:** forest management, energy wood, fertilization, $CO_2$ emissions, biomass

**ACKNOWLEDGEMENTS**

This study was funded by the Finnish Cultural Foundation, the Graduate School in Forest Sciences, the School of Forest Sciences of the University of Eastern Finland (UEF) and the Finnish Forest Research Institute, Eastern Finland Regional unit, Joensuu (FFRI) which all are gratefully acknowledged. I would also like to express my gratitude for the support provided for this work by the Metsäenergia - Project carried out in the collaboration between UEF and FFRI.

I am grateful to my supervisors Prof. Seppo Kellomäki at the School of Forest Sciences (UEF) and Prof. Antti Asikainen at Finnish Forest Research Institute and co-supervisor Docent Heli Peltola at the School of Forest Sciences (UEF). They have always encouraged me and given valuable comments and criticism during the progress of this study.

I would also like to thank Dr. Antti Kilpeläinen, Dr. Ane Zubizarreta Gerendiain, Docent Pertti Pulkkinen, and Mr. Harri Strandman for their valuable contribution for Papers as co-authors. Mr. Jarmo Pennala and Ms. Marja Kuskelin from the University of Eastern Finland and Pirita Lohela from the Finnish Forest Research Institute are also thanked for helping in the field work and laboratory measurements for datasets used in Paper I. Additional thanks go to Dr. David Gritten for revising the English of the text for individual Papers and the PhD thesis summary. I also wish to express my appreciation and warm thanks to the pre-examiners of this thesis, Professor emeritus Sune Linder at Southern Swedish Forest Research Centre and Professor Lauri Valsta at University of Helsinki for their valuable comments.

Finally, I want to thank my husband Jukka, and my children Roope, Rasmus, René, Rufus, Ronja-Ursula and Rebecca-Ulrika for their support and patience.

Joensuu, May 2011

Johanna Routa

**LIST OF ORIGINAL ARTICLES**

This thesis is a summary of the following papers, which are referred in the text by the Roman numerals I-IV. The papers are reproduced with the kind permission of the publishers.

**I** Kilpeläinen, A., Routa, J., Peltola, H., Zubizarreta, A., Pulkkinen, P. and Kellomäki, S. 2010. Effects of genetic entry and competition on above ground biomass production of Norway spruce grown in southern Finland. Forest Ecology and Management 259: 2327-2332.
doi.org/10.1016/j.foreco.2010.03.005

**II** Routa, J., Kellomäki, S., Peltola, H. and Asikainen, A. 2011. Impacts of thinning and fertilization on timber and energy wood production in Norway spruce and Scots pine: scenario analyses based on ecosystem model simulations. Forestry 84: 159-175.
doi:10.1093/forestry/cpr003

**III** Routa, J., Kellomäki, S., Kilpeläinen, A., Peltola, H. and Strandman, H. 2011. Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. Global Change Biology Bioenergy, in Press.
doi: 10.1111/j.1757-1707.2011.01106.x.

**IV** Routa, J., Kellomäki, S. and Peltola, H. 2011. Impacts of intensive management and landscape structure on timber and energy wood production and net $CO_2$ emissions from energy wood use of Norway spruce. Bioenergy Research, in Press.
doi 10.1007/s12155-011-9115-9.

Johanna Routa was the main author for Papers II-IV and had the main responsibility for all calculations and analyses as well as writing. She also performed the data analyses for Paper I, but the results were written up jointly with the co-authors. The co-authors of different Papers have improved the work by commenting on the manuscripts.

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# 1. INTRODUCTION

## 1.1 Background of the work

In 2007 the Council of Europe accepted the proposal of the European Commission that the EU countries should produce 20% of their energy using renewable sources, including bioenergy, by 2020. Each member state has their own target, for example, Finland should produce 38% of its consumed energy from renewable sources by 2020. In this respect, the role of forests is important as currently about 80% of the bioenergy production in Finland is based on wood. The annual consumption of forest chips in heating and power plants has already increased since the year 2000 over five-fold, up to 5.4 million $m^3$ per year by 2010 (Ylitalo 2010). In regard to forest chips, the current target given by the Finland's National Forest Programme (2008) is to use 8-12 million $m^3$ $a^{-1}$ by 2020. On the other hand, the Ministerial Working Group of the Finnish Government for climate and energy policy has set an even higher target, up to 13.5 million $m^3$ $a^{-1}$ by 2020. The technical harvesting potential of forest chips could be up to 16 million $m^3$ per year in Finland (Helynen et al. 2007). About 45% of this amount could be obtained from pre-commercial and first commercial thinning based on small-dimensioned wood (Hakkila 2004).

Currently, about 60% of energy biomass is harvested in final fellings, including mainly the top part of stems, stumps and coarse roots. The remaining energy biomass is harvested related to tending of sapling stands (pre-commercial thinning at the height 3-5 m), energy wood thinning (at the height of 8-12 m) and other thinning. This biomass includes foliage, branches, and stems of removed trees. The role of first and other commercial thinnings is nowadays considerably smaller than others. However, due to the changing criteria of harvesting subsidies, the role of first thinning is likely to increase. In harvesting of energy biomass, the nutrients bound in biomass are removed outside the ecosystem. Especially, in the biomass originating from pre-commercial and first thinnings the nutrient concentrations in biomass are high. Therefore, such cuttings should be used only on the most fertile sites in order to avoid any growth reductions (Recommendations for forest management in Finland 2006, Kuusinen and Ilvesniemi 2008).

The harvesting of energy biomass (logging residues) is usually integrated with the harvesting of timber (pulpwood, sawlogs). This makes the production of energy biomass cost-efficient. When producing timber such as sawlogs, management usually aims at fast diameter growth. This is achieved by the use of lower stocking than that maximizing biomass production. It is still an open question regarding how to optimize management (e.g. spacing, timing and intensity of thinnings, and rotation length) over a rotation in order to integrate the production of timber and energy wood in a sustainable way. For example, the stand density preferred in the early phase of stand development when aiming for timber production is probably too low for the efficient production of energy biomass. The rotation length is also currently determined by timber production, because its value is much higher than that of energy biomass (Recommendations for forest management in Finland 2006). In this regard, it is important to determine which kind of management regimes could produce more energy biomass without endangering simultaneous timber production.

The current age class distribution in the Finnish forests is such that the need for pre-commercial and commercial thinnings will increase in the near future (Rummukainen et al.

2003). In the long run, there is also a need to manage forests in a way that the production of forest biomass for energy use is sustainable and environmentally sound. In this respect, proper tree species (or genotype) selection and stand density in the early phase of stand development provide the basis to produce energy biomass. In this way, also carbon sequestration in forests may be increased. It can also be enhanced through nitrogen fertilization, which also helps to compensate for the loss of nutrients removed in energy biomass. In Finland, the forest growth in upland conditions is greatly limited by the limited supply of nitrogen as demonstrated by wood programs in the 1960s and 1970s (Kukkola and Nöjd 2000).

Energy production based on forest biomass could, in general, be considered to be carbon neutral in the long term, because combustion of biomass releases the same amount of carbon dioxide ($CO_2$) as has been captured in growth. However, in the short term, $CO_2$ and other greenhouse gases (GHG) are emitted from fossil fuels used in different phases of biomass production and energy supply. The rotation length and harvest of biomass affect carbon stocks in trees and soil in forest ecosystems (Aber et al. 1978, Cooper 1983, Liski et al. 2001), but these effects are in general ignored in the analyses of the GHG balance of bio-energy systems (Jungmeier and Schwaiger 2000, Bradley 2004, Cowie 2004). Timber used in wood products also affects the capacity of forests to mitigate the carbon emissions. Recently, the carbon neutrality of renewable biomass has been questioned owing to high indirect greenhouse gas emissions, which are related to the land use and its changes in producing bioenergy (Searchinger et al. 2008, Melillo et al. 2009).

Globally, forest soils are a remarkable carbon stock (Jobbágy and Jackson 2000, Smith et al. 2006), especially in the boreal zone (Liski et al. 2002). Carbon stock in the boreal zone in vegetation and soil is 559 Gt C (IPCC 2000). The growth and removal of forest biomass in harvesting determine the carbon stock above ground, while litter accumulating and decomposing in soil determine the carbon stock in the soil. In harvesting of biomass for energy use, the total carbon balance in the forest ecosystem (trees, soil) is disturbed above the ground. This is the case also in the soil because the litter accumulation on the soil will substantially decrease due to the harvesting of branches and foliage, stumps and roots, and top parts of or whole stems. Consequently, the amount of organic matter in the soil (SOM) decreases in the long term. This may affect to nutrient balance and the growth in the future.

In forest management, cost-efficiency affects the choice of management strategy for producing timber and biomass. Cost-efficiency measures the costs needed to achieve a given goal. Regarding the biomass harvest in energy wood thinning, the harvest costs are especially high, because the handling of small-dimensioned trees does not allow the use of the full capacity of the logging machines with a consequent decrease in the productivity of work (Kärhä et al. 2004, Laitila 2008). The profitability of thinning of energy wood is also dependent on the energy wood price as well as subsidies. Cost-efficient harvesting is, however, a precondition for the utilization of small-sized trees for energy purposes. Currently, pre-commercial thinning operations are subsidized also for silvicultural reasons, which support energy wood harvesting (Laitila 2008).

At a regional level, the structure of forest landscape (e.g. species and age class distribution) affects the timber yield and carbon stocks in the forest ecosystems (Garcia-Gonzalo et al. 2007). Newly regenerated sites lose carbon, whereas young stands gain carbon (Jarvis et al. 2005). In addition, in maturing stands, the carbon gain is reduced along with the declining growth and old stands may even lose carbon. Therefore, the sustainable management for timber production and carbon sequestration point of view at the forest landscape level requires that the stands represent different stages in the life cycle of trees in order to simultaneously sustain timber and biomass production and carbon sequestration in the forest ecosystem (Garcia-Gonzalo et al. 2007). On the other hand, sustainable management of forest requires that forest ecosystems should be management in a such way that in addition to forest productivity (affects also carbon sequestration) and regeneration success, also vitality of forests and their diversity are safeguarded as was stated by Ministerial Conference on the Protection of Forests in Europe 1993. It also means that economical, ecological and social aspects are considered simultaneously. In this way, the forests could supply various ecosystem services at the same time, such as timber and energy biomass as well as non-timber products and multiple use of forests, while safeguarding biological diversity of forest ecosystems (see e.g. Vierikko et al. 2008).

Compared to experimental studies, ecosystem modelling provides an option to study the long-term functioning and structure of the forest ecosystems under varying management. In this respect, growth and yield models are essential tools in forest management, e.g. they allow the analyses of the sensitivity of stem wood production to different silvicultural treatments for different species (e.g. spacing, thinning, fertilization) and varying environmental conditions (e.g. Kellomäki et al. 1992, Hynynen et al. 2005). Such models could also be used in the identification of optimal management in forest planning (Hynynen et al. 2005, Hyytiäinen et al. 2006). This holds also for the research questions on: (i) how to sustainably use forest biomass in energy production, (ii) how this affects the long-term dynamics of the forest ecosystems, and (iii) how the use of forest biomass can reduce the GHG emissions in energy production.

In the above context, the environmental life cycle assessment (LCA) can also be used to analyze the environmental impacts of production of timber and energy biomass over the whole life cycle. The LCA considers the material and energy requirements and emissions to the air, water and soil allowing the assessment of environmental impacts of the land use (Consoli et al. 1993, Lindfors et al. 1995). However, its weakness is that the results have a low spatial and temporal resolution, and that social and economic aspects are not taken into account (Owens 1997, Udo de Haes et al. 2004). Despite these limitations, LCA facilitates the comparative analysis of how different management strategies in the production of energy biomass may affect the forest environment and helps to determine what are the benefits and drawbacks compared to the use of fossil fuels (Cherubini et al. 2009).

## 1.2 Aims of the work

The main aim of this thesis was to study the effects of forest management on the sustainability of integrated timber and energy wood production in Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) based on scenario analyses using an ecosystem model. In this context the effects of forest management on the total stem wood production, timber and energy wood production and their implications to net present value (NPV) and net $CO_2$ emissions of use of energy wood were considered. In addition, the effects of the genetic entry on above-ground biomass production of Norway spruce, based on experimental data, was studied. More specifically, the research aims of different Papers (Papers I-IV) were as follows:

- To analyze the effects of the genetic entry on above-ground biomass production of Norway spruce grown in an experimental trial located in southern Finland (Paper I).

- To analyze the effects of thinning and fertilization with varying pre-commercial stand density on timber and energy wood production and the net present value (NPV) over a rotation length of 80 years for Norway spruce and Scots pine (Paper II).
- To analyze the effects of forest management on the production of stem wood and energy wood and the net $CO_2$ emissions of energy wood use when aiming at integrated production of timber and energy wood over a rotation length of 80 years for Norway spruce and Scots pine (Paper III).
- To analyze the effects of intensive management (i.e. especially effects of N fertilization and rotation length) and the structure of forest landscape on the timber and energy wood production and the net $CO_2$ emissions of the energy wood use in Norway spruce (Paper IV).

The effects of abiotic and biotic risks related to energy wood harvesting and removal or leaching of nutrients were not included in this study.

## 2. MATERIAL AND METHODS

### 2.1 Outlines of the work

This work is based on both experimental and model-based analyses (Figure 1). In the experimental work, the effects of Norway spruce clones on the above-ground biomass were studied in an experimental trial located on medium fertile site in central Finland. This was done in order to identify the production potentials of different clones of Finnish and foreign origins (Paper I). In the model-based analyses, the effects of pre-commercial stand density, thinning regimes, nitrogen (N) fertilization and rotation length on the total amount of timber and energy biomass and NPV in Norway spruce and Scots pine on site types with different fertility was studied. At the same time, the $CO_2$ emissions as a result of the use of energy biomass was studied for Norway spruce grown on the medium fertile (*Myrtillus* type, MT) and fertile sites (*Oxalis-Myrtillus* type, OMT) and Scots pine grown on the medium fertile (MT) and less fertile sites (*Vaccinium* type, VT). The model based analyses were done at the stand level for both species and at the landscape level for Norway spruce (Papers II-IV).

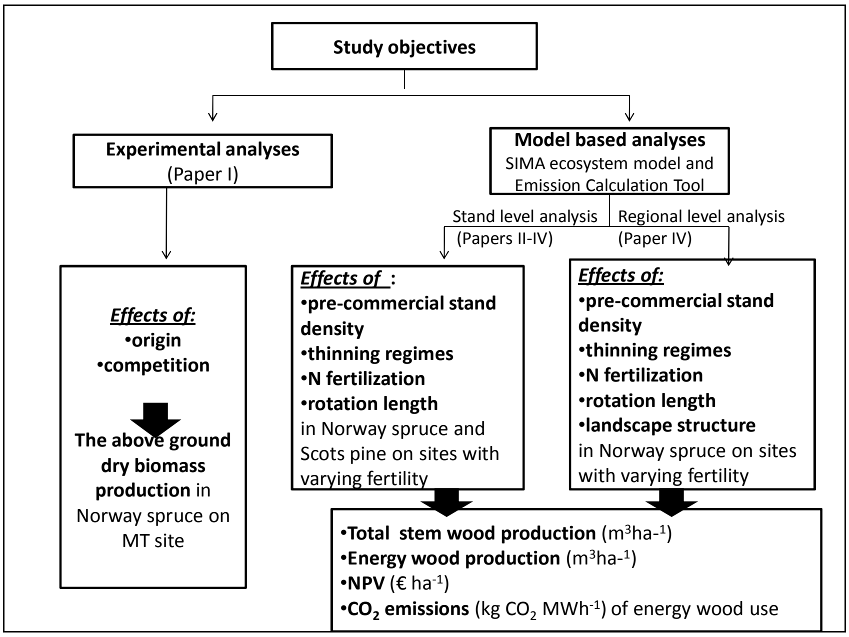



**Figure 1.** Outlines of the work.

## 2.2 Analysis of experimental data

The material used in Paper I represents a Norway spruce clonal trial established in 1979 by the Finnish Forest Research Institute (test 690/01) in Kangasniemi, southern Finland (61°59’3N, 26°38’54E). The trial is situated on a MT site with an initial spacing of 2 m × 2 m (i.e. 2500 trees ha $^{-1}$). No thinning was done before harvesting the sample trees for this study

In total 20 Norway spruce clones were harvested, representing seven provenances or provenance-hybrids (i.e. origins). Altogether, ten of the 20 clones originated from the crosses between the Finnish plus trees (F×F) representing different breeding regions in Finland. In addition, two clones originated from Russian parent trees (R×R), while the remaining eight clones represented provenance-hybrids, i.e. crosses between the Finnish trees with German (four clones, F×G), Swiss (one, F×S), Latvian (one, F×L), Ukrainian (one, F×U), or Estonian (one, F×E) trees.

Five randomly selected sample trees were harvested for each clone, and their height and diameter at breast height (dbh) and at 6 m were measured. Additionally, the crown diameter of the sample trees was measured based on the orthogonal projection, both in the north–south and west–east direction. Furthermore, the diameter at breast height, tree height and crown diameter for the eight nearest trees surrounding each sample tree (in a square plot, sample tree located in the middle) were measured. The fresh mass of the crown (i.e. dead and living branches and needles) was weighed for each sample tree at the site. Moreover, one sample branch from the middle of the living crown was taken from each sample tree for estimating dry mass of the whole crown and separately for the needles and branches. For determining the stem dry mass, sample discs were taken at a stem height of 1-1.3 m from each sample tree.

The weight of the sample branches and the share of branch wood and needles were measured under laboratory conditions. Furthermore, the weight and dimensions of sample discs were measured and the average wood density (dry) calculated. Stem volume was calculated with the functions developed by Laasasenaho (1982). Additionally the dry mass of the stem for each sample tree was calculated based on the measurements (Paper I).

The mean (μ), standard deviation (σ) and the phenotypic coefficient of variation ($CV = \sigma \times 100/ \mu$) were calculated for each biomass component and for the whole biomass of each clone. Furthermore, the average harvest index for each clone was calculated, i.e. a ratio between the dry mass of stem and the total above ground dry biomass (including needles, branches, and stem wood). In order to analyze the effects of neighboring trees on the biomass growth of the sample trees (target trees), competition index formulated by Schütz (1989) was applied (for details see, Paper I). To identify the clonal effects on the biomass production, the General Linear Model (GLM) procedure (SPSS for Windows, 16.0, Chicago, IL) was used, with the competition index as a covariate (LSD test, $p < 0.01$). Since the clones were harvested from five different blocks, the block effect was also included in the analyses as a random factor. In addition, different biomass components were also calculated for comparison based on some Finnish and Swedish biomass component models to determine how well these models could predict the biomass of clonal material.

### 2.3 Outlines of the models and their simulations

*SIMA model*

The simulations in Papers II - IV were done by employing the ecosystem model SIMA (Kellomäki et al. 1992, Kolström 1998, Kellomäki et al. 2008), which is a gap-type model utilizing a time step of one year. In the model, the growth of a tree is based on diameter growth, which is the product of potential diameter growth and environmental factors. The model incorporates four subroutines describing the environmental factors regarding temperature sum (degree days, d.d. with +5 $^{o}$C threshold), within-stand light conditions, soil moisture and availability of nitrogen (Figure 2). The dynamics of available nitrogen is determined by the amount of nitrogen released and immobilized in decomposition of the soil organic matter, as well as that deposited from the atmosphere and added as fertilizer (Kellomäki et al. 1992).

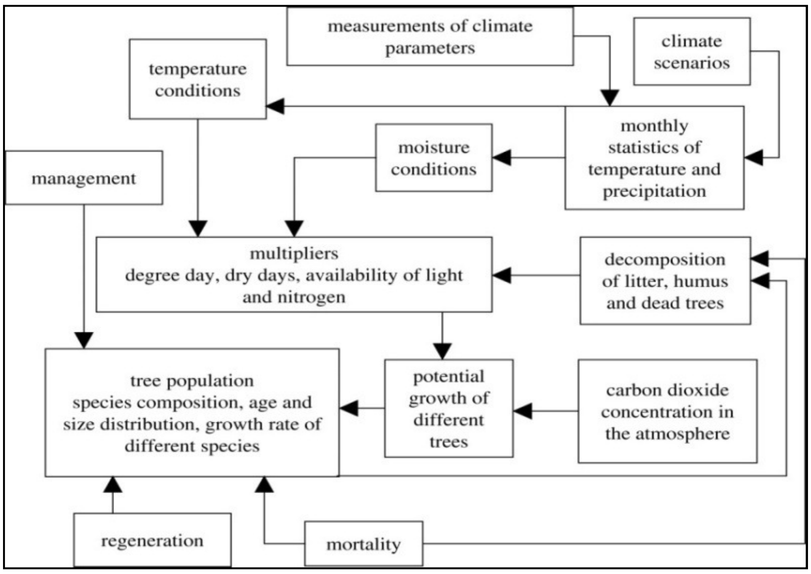



**Figure 2**. Outlines of the SIMA model used in the simulations (Kellomäki et al. 2008).

A procedure for management includes regeneration with chosen tree species, initial stand density, thinning, nitrogen fertilization, rotation length and harvesting of timber (saw logs and pulp) and energy biomass (foliage, branches, stumps and top part of stem not suitable for timber). The effect of total amount of fertilizer (NT, kg $ha^{-1}$) is allocated over several years so that its effect will gradually reduce and finally disappear.

The SIMA model has been previously validated in detail, by e.g. Kellomäki et al. (2008), who found that the simulated growth of forests was in reasonable agreement with measured values based on the measurements for the permanent sample plots of the National Forest Inventory (NFI). In regard to the growth response of trees to nitrogen deposition, fairly good agreement between predicted and measured values was found by Mäkipää et al. (1998). The performance of the SIMA model was further examined in Paper II by comparing the parallel simulations for the growth of Norway spruce and Scots pine stands by the SIMA model and the statistical growth and yield model Motti (Hynynen et al. 2002). A fairly good correlation between the simulated growth values for the Motti and SIMA models was found regardless of tree species (Paper II: Figure 3). The performance of the SIMA model was also analysed in Paper III for ten Forest Centers (administrative forest regions) in southern Finland based on the measurements for the permanent sample plots of the NFI for the years 1996 and 2003 (Finnish Statistical Yearbook of Forestry 2005). A close correlation between the measured and the simulated values was found, regardless of the tree species.

*$CO_2$ Emission Calculation Tool*

In calculating the net carbon dioxide emissions ($C_{net}$), all the main phases in the forest production were taken into account, starting from nursery production and ending at the yard of the power plant (energy wood) (Figure 3). This was done using the Emission Calculation

Tool developed by Kilpeläinen et al. (2011). The calculations were done on an annual basis (g $CO_2$ $m^3$ $a^{-1}$) as indicated by Equation (1), where ($C_{net}$) is a sum of the carbon uptake in growth ($C_{seq}$) and the carbon emissions from management and harvest ($C_{man}$), decomposition of soil organic matter ($C_{decomp}$) and from the burning of energy biomass ($C_{harv}$). In the calculations, the uptake ($C_{seq}$) is shown as negative values (carbon is flowing from atmosphere to forest) and the emissions ($C_{man}$), ($C_{decomp}$), and ($C_{harv}$) as positive values (carbon is flowing from forests to atmosphere).

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

In the LCA calculations, the following output variables of the SIMA model were used: (i) the annual growth (stem, branches, foliage, coarse roots and fine roots) ($C_{seq}$), (ii) the amount of biomass harvested ($C_{harv}$) in energy wood thinning (energy biomass in terms of foliage, branches and stems) and in commercial thinnings (timber) and final felling (energy biomass, timber, stumps and roots). Furthermore, the model simulations produced the annual litter fall for the decomposition and consequent emissions of carbon from soil ($C_{decomp}$) to be used in the LCA analyses (Kilpeläinen et al. 2011).

In addition, the emissions from the combustion of energy wood were considered over the whole simulation period. Harvesting loss of needles was assumed to be 30%. Finally, the net emissions for energy wood were converted into $CO_2$ emissions per unit of energy (kg $CO_2$ $MWh^{-1}$). In this calculation, the energy content of the fuel (diesel) was taken as 38.6 MJ $l^{-1}$ and the carbon content as 0.857 kg $l^{-1}$. A wood density of 400 kg $m^{-3}$ and C content of 50% in the dry biomass were used in the calculations.

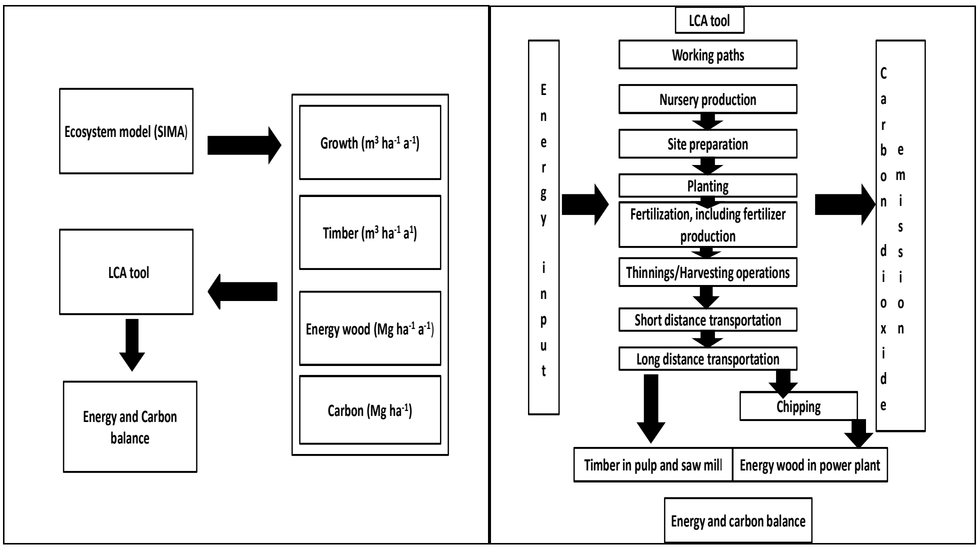



**Figure 3.** System boundaries for calculating carbon and energy balances from forest bio-energy supply chains (modified from Kilpeläinen et al. 2011).

## 2.4 Model based analysis at stand level

The simulations in Papers II-IV were made for the Joensuu region, in central Finland (62.39° N, 29.37° E). The mean temperature sum in this area is 1150-1200 d.d. Simulations were done for Norway spruce on the fertile (OMT) and medium fertile (MT) sites (Papers II-IV), and for Scots pine on the medium fertile (MT) and less fertile sites (VT) (Papers II and III). In the simulations, an annual nitrogen deposition of 6.0 kg ha$^{-1}$ was used based on the long-term mean for the Joensuu region (Järvinen and Vänni 1994). The average breast height diameter of the saplings at the beginning of the simulation was 2 cm, with the stand density varying between 1800 and 4500 seedlings per hectare depending on the management regime in Papers II-III and between 1800 and 3500 seedlings per hectare in Paper IV.

In the simulations, the thinning rules used followed those currently recommended for the different tree species on different site fertility types in central Finland (Recommendations for forest management in Finland 2006). The thinning rules are based on the dominant height and basal area of the trees. Whenever a given basal area threshold at a given dominant height (i.e. the average height of the 100 largest trees) is reached, thinning is done and basal area is reduced to the recommended value. Thinning was done from below regardless of the management regime.

The basic thinning regime aiming at the production of timber included a pre-commercial stand density of 1800-2500 trees ha$^{-1}$ (Papers II-IV). The first commercial thinning was done at the dominant height of 13 m to the density of 900-1000 trees ha$^{-1}$. The corresponding regimes aiming at the integrated production of timber and energy wood included a pre-commercial stand density range from 2500 to 4500 trees ha$^{-1}$ (with the steps of 500 trees ha$^{-1}$). Energy wood thinning was done either at a height of 8 or 10 m to the density of 1800 trees ha$^{-1}$ (Papers II-III) or 1300 trees ha$^{-1}$ (Paper II). In Paper IV, the pre-commercial stand density ranged for energy wood management cases from 3000 to 3500 trees ha$^{-1}$ (Table 1). In this case, the energy wood thinning was done at the dominant height of 10 m to the density of 1800 trees ha $^{-1}$. The second and third (if required) thinning was done following the thinning recommendations based on the basal area and dominant height (Papers II-IV). In energy wood thinning, all the industrial-size wood was used for energy and logging residues were harvested (Papers II-IV).

In Paper II, the N fertilization amount (100, 150, and 200 kg N ha$^{-1}$) and the number of applications (none, two or three times during the rotation) varied depending on the management regime. It was done at the time of first thinning at a dominant height of 8, 10, or 13 m, and thereafter once or twice at intervals of 12 and 10 years depending on the management regime. In Papers III and IV, the fertilization was 150 kg N ha$^{-1}$. In Paper III, the number of fertilizer applications varied depending on the management regime (none, two or three times during the rotation). In Paper IV, fertilization was done twice during the rotation or not at all.

The fixed simulation time of 80 years was used in Papers II and III regardless of the management regime to determine how large differences between different management regimes could exist over the rotation in regard to the variables analyzed. The rotation length of 80 years is also widely used in forestry for Scots pine and Norway spruce in Finland. However, in Paper IV, the rotation length varied between 40 to 120 years, in order to study the sensitivity of results with regards to rotation length.

**Table 1.** Simulations in Papers II-IV.

| Study | Species | Site types | Pre-commercial stand density (trees ha$^{-1}$) | Stand density (trees ha$^{-1}$) after first commercial thinning with $h_{dom}$, m | Rotation length, years | Fertilization | Study level |
|---|---|---|---|---|---|---|---|
| II | Norway spruce | OMT, MT | *basic:* 1800 or 2300 | 900 with $h_{dom}$ 13 | 80 | 0, 2, or 3x100-200 kg N ha$^{-1}$ | stand level |
| | | | *integrated:* 2500-4000 | 1300 or 1800 with $h_{dom}$ 8 or 10 | | | |
| III | Norway spruce | OMT, MT | *basic:* 1800 or 2300 | 900 with $h_{dom}$ 13 | 80 | 0, 2, or 3 x 150 kg N ha$^{-1}$ | stand level |
| | | | *integrated:* 2500-4000 | 1800 with $h_{dom}$ 8 or 10 | | | |
| IV | Norway spruce | OMT, MT | *basic:* 1800 | 900 with $h_{dom}$ 13 | 40, 60, 80, 100 or 120 | 0 or 2 x 150 kg N ha$^{-1}$ | stand level, landscape level |
| | | | *integrated:* 3000 or 3500 | 1800 with $h_{dom}$ 10 | | | |
| II | Scots pine | MT,VT | *basic*: 2000 or 2500 | 1000 with $h_{dom}$ 13 | 80 | 0, 2 or 3 x 100-200 kg N ha$^{-1}$ | stand level |
| | | | *integrated:* 3000-4500 | 1300 or 1800 with $h_{dom}$ 8 or 10 | | | |
| III | Scots pine | MT,VT | *basic:* 2000 or 2500 | 1000 with $h_{dom}$ 13 | 80 | 0, 2 or 3 x 150 kg N ha$^{-1}$ | stand level |
| | | | *integrated:* 3000-4500 | 1800 with $h_{dom}$ 8 or 10 | | | |

The net present value (NPV, € ha$^{-1}$) using different management regimes was also considered by discounting all the incomes (incl. pulpwood, saw logs, and energy wood) and costs for management and harvesting over time from the start of the simulation period. The stumpage prices and the costs of management operations used in Papers II and IV were based on the average values over the period 2000-2008 for the provenance of North Karelia, Finland (Metinfo - forest information services). For Norway spruce and Scots pine, the stumpage prices of 48.6 and 21.3 € m$^{-3}$ and 49.1 and 13.6 € m$^{-3}$ were used for sawlogs and pulp.

In this work possible costs caused by pre-commercial thinning were evaluated based on the expected number of trees removed in cutting. If the removal was expected to be 1000 trees $ha^{-1}$ or less, the cost was 50% less compared to the removal of 3000 trees $ha^{-1}$ or larger (Ylimartimo and Heikkilä 2003). Regeneration costs were taken as the same regardless of the management regime for each tree species. They included costs for soil preparation (mounding) and planting of 2500 trees $ha^{-1}$ in Norway spruce and soil preparation (scarification) and seeding in Scots pine. Natural regeneration was also expected to happen in planted Norway spruce stands, increasing the pre-commercial stand density and, thus, also allowing the consideration of energy wood production. However, for simplicity it was expected that any natural regeneration was only for Norway spruce, which is not necessarily the case in practice (i.e. broadleaves often establish naturally in young coniferous stands, see Saksa and Kankaanhuhta 2007).

The stumpage price of energy wood was 4 € $m^{-3}$ in Paper II and 5 € $m^{-3}$ in Paper IV. In the energy wood thinning, all the removal, including industrial-sized stem wood, was considered as energy wood. A sensitivity analysis was also made for the effects of optional price of energy wood (3-5 € $m^{-3}$) and for the effects of different discount rates of 1-4% in Paper II.

## 2.5 Model based analyses at landscape level

The landscape-level analysis was done only for Norway spruce. The focus was on the effects of landscape structure on the timber production, NPV and $CO_2$ emissions. The landscape structure varied in terms of the age class distributions (0-20 years (sapling stands), 21-40 years, 41-60 years and 61-80 years and >80 years) (Table 2). The simulations for a hypothetical forest area of 100 ha were done assuming the following distributions: A) dominated by intermediate age classes (normal distribution), B) dominated by young age classes (left-skewed distribution) and C) dominated by old age classes (right-skewed distribution). Simulations were done also assuming that the whole forest area consisted of OMT or MT sites.

**Table 2.** Age class distributions used in the simulations and the percentage of area occupied by each of the age class groups.

| Age class distribution | Age class groups | | | | |
|---|---|---|---|---|---|
| | 0-20 years | 21-40 years | 41-60 years | 61-80 years | > 80 years |
| | (%) | (%) | (%) | (%) | (%) |
| A) normal | 15 | 30 | 30 | 20 | 5 |
| B) left-skewed | 45 | 25 | 15 | 10 | 5 |
| C) right-skewed | 5 | 10 | 15 | 25 | 45 |

# 3. RESULTS

### 3.1 Variation in above-ground biomass production in different Norway spruce clones

In Paper I the effects of genetic entry and competition on the above-ground dry biomass production (i.e. stem wood, crown and harvest index) was studied for 20 Norway spruce clones grown, including both Finnish and Russian clones, as well as provenance-hybrids clones. Differences existed between clones in the dry mass production of stem wood and in total above-ground production, but not in dry mass of crown or in harvest index. However, there was a large variation also within the clones. The competition caused by neighboring trees also significantly affected above-ground dry biomass and its components over all clones (no differences between the clones).

In general, the clones of the Finnish origin had the largest above-ground biomass (i.e. stem wood, needles, and branches) production (e.g. clone F430), but one German clone (G477) showed also high production (see Paper I: Figure 1). The clone F430, showing the largest dry stem mass also had the largest diameter at breast height and tree height (though slightly lower mean wood density than the average over all the clones). The average production of above-ground biomass over all clones with 2500 trees $ha^{-1}$ at the age of 28 was calculated to be a total of 97 Mg of dry mass per hectare. If about 1500 trees per ha was harvested from the trial in the first commercial thinning for energy wood (about 1000 trees $ha^{-1}$ are left after thinning), the total recovery of dry biomass per hectare could be 58 Mg $ha^{-1}$ for all the clones. Some of the clones showed especially high potential for the biomass recovery in energy wood thinning. For example, the most productive clone (F430) had above-ground biomass 71% above the average for all the clones.

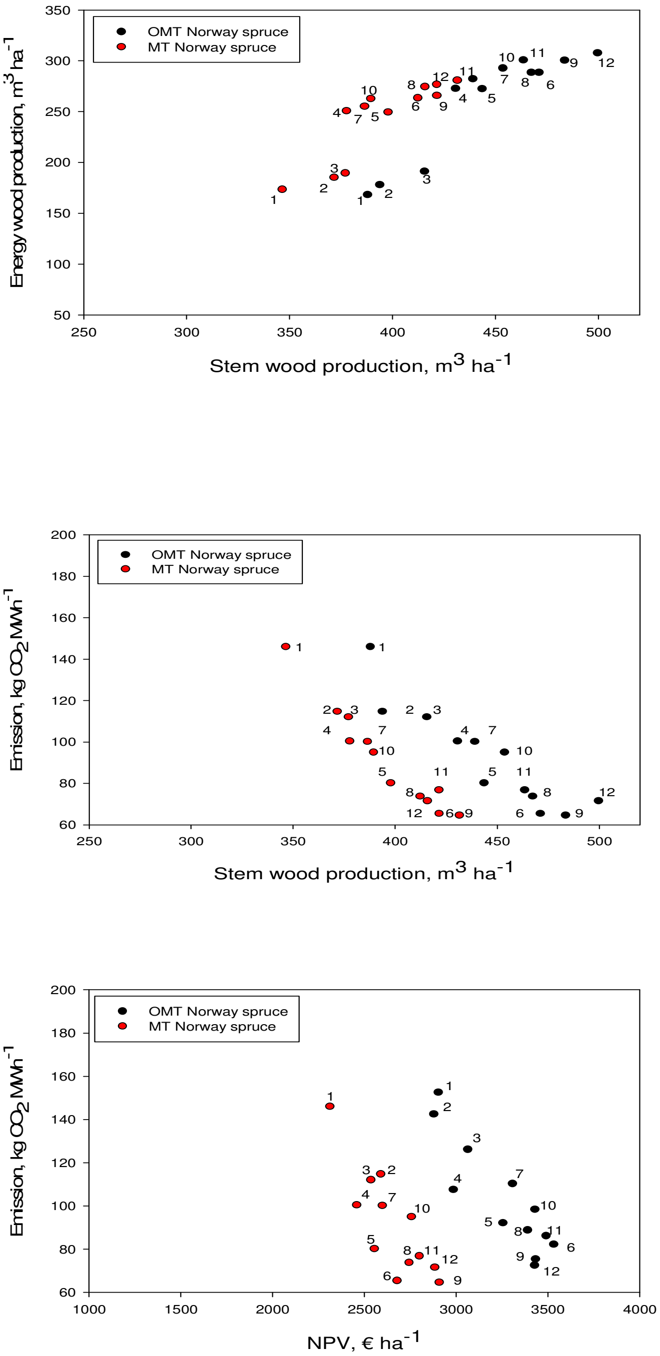
When comparing the measured above-ground biomass components against the corresponding estimations based on biomass models used in comparison, it was found that the dry mass of needles and stem could be estimated well for individual trees with the available biomass models. This was opposite to the dry mass of branches.

### 3.2 Sustainability of timber and energy wood production in Norway spruce and Scots pine at stand level

**Stem wood and energy wood production.** In general, the management with higher pre-commercial stand density than that used in basic management and N fertilization clearly increased stem wood production (i.e. sawlogs, pulp, and small-sized stem wood) over the rotation both in Norway spruce and Scots pine (Figures 4 and 5, see also Papers II-IV). This was found regardless of site fertility (Papers II-IV) and rotation length (Paper IV) used in the simulations. Such management also increased energy biomass production, consisting of logging residuals, stump wood and roots, and small-sized stem wood (Figures 4 and 5). However, the total stem wood production and energy wood production were also affected by the timing of energy wood thinning. Fertilization had a positive effect, but the effects of number and amount of N fertilization were negligible on the total stem wood production and energy wood production (Papers II-III).

The effects of N fertilization on the total stem wood production (also on energy wood production) were always higher on less fertile site types regardless of tree species and management applied in otherwise (Paper II). For example, in Norway spruce grown on the MT and OMT sites, the fertilization of 3 x 150 kg N $ha^{-1}$ over the rotation of 80 years increased the total stem wood production on average by 16% and 10%, respectively. As a comparison, in Scots pine grown on the MT and VT sites, the fertilization of 3 x 150 kg N $ha^{-1}$ over the rotation of 80 years increased the total stem wood production by 4% and 17%, respectively (Paper II). When analyzing the effects of rotation length on annual stem wood production in Norway spruce on the OMT and MT sites, it was found that the highest annual stem wood production was obtained with a short rotation length (40 and 60 years, respectively) (see Paper IV: Figure 4).

**Net present value (NPV).** The management with higher pre-commercial stand density than that used in basic management and N fertilization also increased NPV (with interest rate of 2%) over a rotation of 80 years, both in Norway spruce and Scots pine regardless of site fertility type (Figures 4 and 5, see also Paper II). This was related to earlier incomes. For example, in Norway spruce, the effects of fertilization on the NPV were larger on the MT sites compared to OMT sites as was found for stem wood production. As a comparison, in Scots pine the effects of fertilization on NPV were negligible on the MT sites, opposite to the VT sites. Furthermore, NPV per year was also highest in Norway spruce when the rotation length of 60 years was applied regardless of site fertility type and interest rate (1-4%) used (see Paper IV: Figure 6).




***1*** Basic

***2*** Basic, 2 x 150kg N ha-1

***3*** Basic, 3 x 150kg N ha-1

***4*** Integrated, dense pre-commercial stand

***5*** Integrated, dense pre-commercial stand,2 x 150kg N ha-1

***6*** Integrated, dense pre-commercial stand, 3 x 150kg N ha-1

***7*** Integrated, very dense pre-commercial stand

***8*** Integrated, very dense pre-commercial stand, 2 x 150kg N ha-1

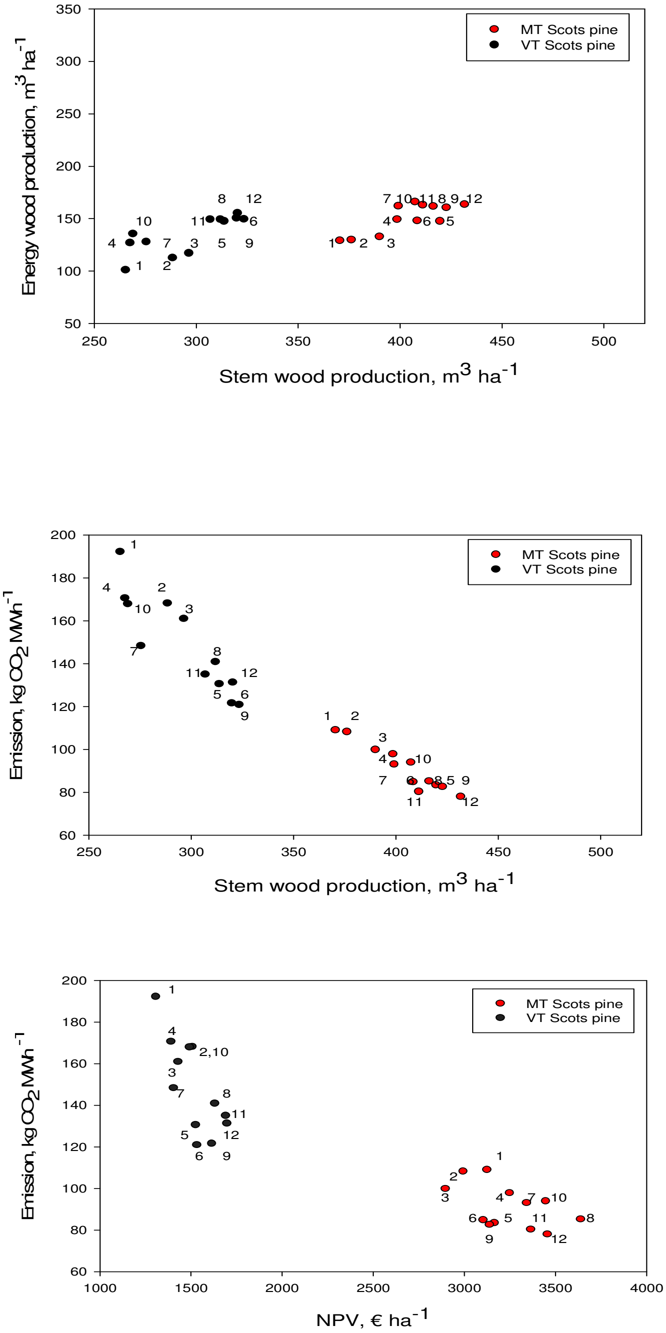
***9*** Integrated, very dense pre-commercial stand, 3 x 150kg N ha-1

***10*** Integrated, extremely dense pre-commercial stand

***11*** Integrated, extremely dense pre-commercial stand, 2 x 150kg N ha-1

***12*** Integrated, extremely dense pre-commercial stand, 3x150kg N ha-1

**Figure 4.** Relations between stem wood and energy wood production (above), effect of management on stem wood production (saw logs, pulp and small-sized stems for energy wood) and the $CO_2$ emissions (middle), effects of management on NPV € ha$^{-1}$ (2%) and the $CO_2$ emissions (kg $CO_2$ MWh$^{-1}$ ) (below) in Norway spruce grown on fertile and medium fertile sites.




***1*** Basic

***2*** Basic, 2 x 150kg N ha-1

***3*** Basic, 3 x 150kg N ha-1

***4*** Integrated, dense pre-commercial stand

***5*** Integrated, dense pre-commercial stand,2 x 150kg N ha-1

***6*** Integrated, dense pre-commercial stand, 3 x 150kg N ha-1

***7*** Integrated, very dense pre-commercial stand

***8*** Integrated, very dense pre-commercial stand, 2 x 150kg N ha-1

***9*** Integrated, very dense pre-commercial stand, 3 x 150kg N ha-1

***10*** Integrated, extremely dense pre-commercial stand

***11*** Integrated, extremely dense pre-commercial stand, 2 x 150kg N ha-1

***12*** Integrated, extremely dense pre-commercial stand, 3 x 150kg N ha-1

**Figure 5.** Relations between stem wood and energy wood production (above), effect of management on stem wood production (saw logs, pulp and small-sized stems for energy wood) and the $CO_2$ emissions (middle), effects of management on NPV € $ha^{-1}$ (2%) and the $CO_2$ emissions (kg $CO_2$ $MWh^{-1}$ ) (below) in Scots pine grown on medium fertile and less fertile sites.

**Net $CO_2$ emissions.** Also in the case of net $CO_2$ emissions, the increase in pre-commercial stand density compared to that used in basic management and application of N fertilization clearly decreased the net $CO_2$ emissions in energy production over rotation both in Norway spruce and Scots pine (Figures 4 and 5) (see also Papers III-IV). This was found regardless of the site fertility type (Papers III-IV) and rotation length (Paper IV) used in the simulations.

For example, in Norway spruce grown on the OMT and MT sites, the fertilization of 3 x 150 kg N $ha^{-1}$ over the rotation of 80 years decreased the net $CO_2$ emissions per unit of energy on average by 17 and 23%, respectively, compared to corresponding management regimes without fertilization. The corresponding effects on the net $CO_2$ emissions per unit of energy in Scots pine grown on the MT and VT sites were on average 12 and 19%.

The $CO_2$ emissions per energy unit were also affected in Norway spruce by the rotation length (Paper IV). When the rotation length varied from 40 years to 120 years, the emissions varied in the range of 0.98-7.12 kg $CO_2$ $MWh^{-1}a^{-1}$ on the OMT site and in the range of 0.78-8.92 kg $CO_2$ $MWh^{-1}a^{-1}$ on the MT site, respectively. On both sites, the net $CO_2$ emissions per year were the lowest with the rotation lengths of 80 and 100 years (Paper IV: Figure 7). In general, high stem wood production and amount of carbon in the forest ecosystem indicated at the same time on average higher NPV and lower $CO_2$ emissions per energy unit regardless of tree species and site fertility type (Figure 6).

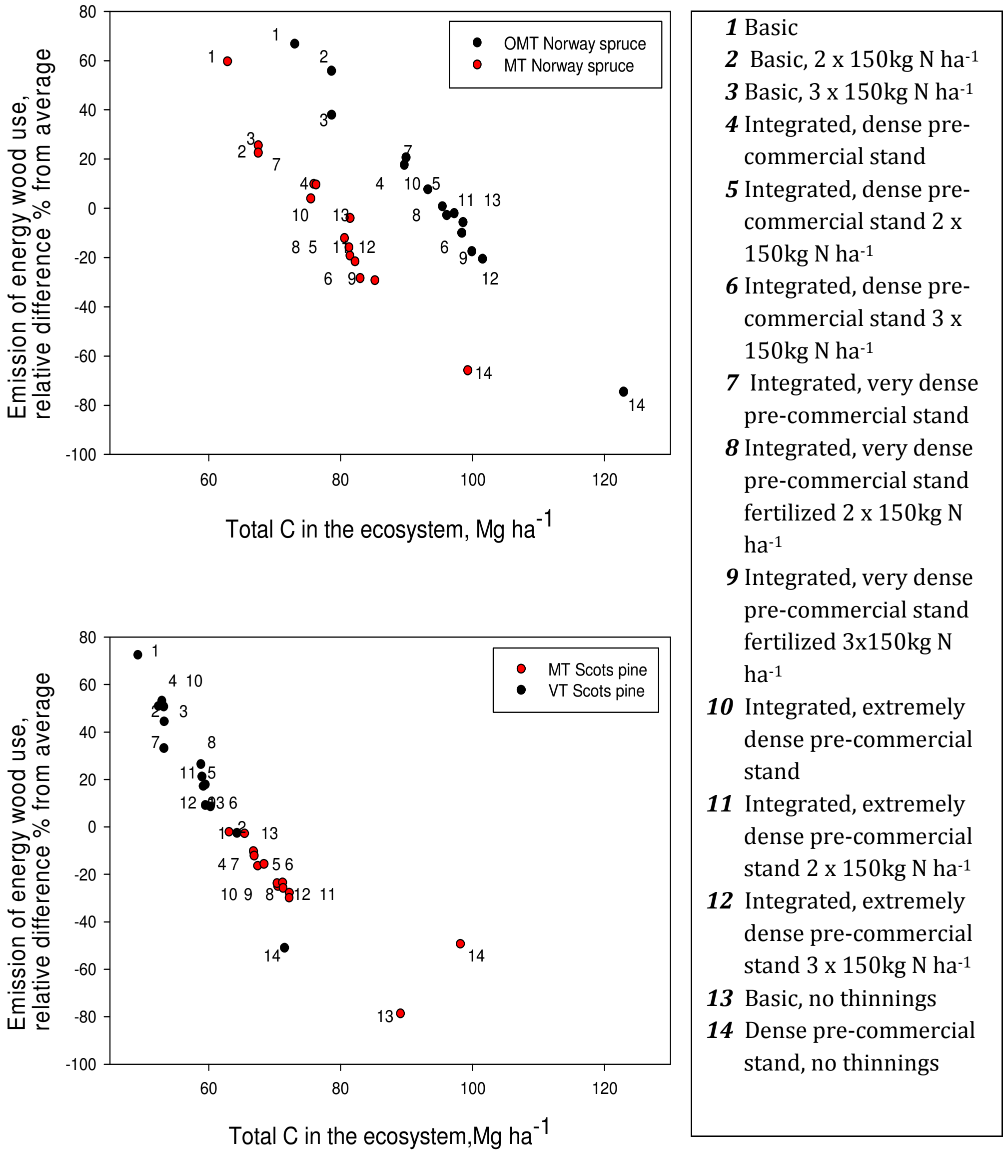



**Figure 6.** Average carbon in the ecosystem over the rotation of 80 years for different management options and the $CO_2$ emissions of energy wood use in Norway spruce (above) and Scots pine (below) stands.

### 3.3 Sustainability of timber and energy wood production in Norway spruce at landscape level

At the landscape-level, the largest average timber and energy wood production ($m^3ha^{-1}a^{-1}$) was obtained when the initial forest landscape was dominated by old mature stands (right-skewed distribution) and the rotation lengths of 60 and 80 years were applied. In the case of the landscape dominated by young age classes (left-skewed distribution), the production of timber and energy wood was the largest with the rotation length of 120 years (see Paper IV: Figure 8). This held for both the landscapes on MT and OMT sites.

The highest NPV (discount rate of 2%) were obtained for the landscape characterized by old stands on the OMT sites regardless of the rotation length, and on the MT sites with the rotation length of 60 and 80 years. When the rotation length of 120 years was used on the MT sites, the highest NPV was obtained when the initial landscape represented the normal age class distribution (see IV: Figure 9).

Regarding the $CO_2$ emissions (kg $CO_2$ $MWh^{-1}a^{-1}$), the lowest values were obtained when the initial landscape represented the age class distribution skewed to the left. This was the case when the rotation lengths of 60 and 80 years were used, regardless of the site fertility of landscape. If the initial landscape represented the normal distribution, the lowest emissions were obtained with the rotation length of 120 years (see Paper IV: Figure 10). Furthermore, the integrated management for timber and energy wood with fertilization gave the lowest emissions over all cases.

## 4. DISCUSSION AND CONCLUSIONS

The main aim of this thesis was to study the effects of forest management on the sustainability of integrated timber and energy wood production in Norway spruce and Scots pine based on scenario analyses using the ecosystem model SIMA, which has been validated in great detail both in earlier studies, but also in this work (Papers II-IV). For this purpose model-based analyses were used to evaluate how the varying pre-commercial stand density and thinning regimes, nitrogen fertilization and rotation length may affect the timber and energy wood production and its profitability (NPV). Concurrently, based on the use of the LCA tool, the effects of management and energy use of biomass on the potential of forests in mitigating the $CO_2$ emissions were studied.. The study dealt mainly with the stand-level analyses for Norway spruce and Scots pine, but also at the forest landscape level of varying age class distributions for Norway spruce. The possible abiotic and biotic risks of energy wood harvest as removal and leaching of nutrients were excluded from this study. Furthermore, experimental data from a clonal trial of Norway spruce was analyzed in this work to determine the potential offered by different clones for above-ground biomass production (Paper I).

Regarding both Norway spruce and Scots pine, the management with higher pre-commercial stand density than that used in basic management and N fertilization clearly increased timber and energy wood production and also net present value (NPV) regardless of site fertility type and rotation length (Papers II-IV). At the same time it decreased the net $CO_2$ emissions of the energy use of biomass (Papers III-IV). The effects of fertilization were especially pronounced when the MT site was considered in Norway spruce and VT site in Scots pine, respectively. The differences observed between VT and MT sites in Scots pine were clearly larger than between the MT and OMT sites for Norway spruce. This result is to the effect of the clearly lower nitrogen content of soil on the VT site than on the MT and OMT sites (Kellomäki et al. 2008).

On the other hand, on the MT sites, Scots pine produced, on average, more stem wood and had higher NPV than Norway spruce when similar kind of management regimes were used in simulations (Paper II). This result is related to the faster growth of Scots pine especially in the early phase of the rotation. These findings are in line also, for example, with work by Mielikäinen (1980, 1985), who showed that Scots pine has, on average, higher annual growth compared to Norway spruce on MT site when rotation length of about 80 years were used in Finnish conditions. On medium fertile sites, higher pre-commercial stand density may be preferred for Scots pine, as it increases the quality of the lower part of the stem due to decreased growth and earlier death of branches near the stem base (e.g. Kellomäki et al. 1999). Based on this study, the increase of pre-commercial stand density compared to that used in basic management will also simultaneously increase the growth and economic profitability of the management (Papers II-IV).

For Norway spruce grown on the OMT and MT fertile sites, the highest annual stem wood production was obtained with the shorter rotation length (40 and 60 years). The annual NPV was the highest with the rotation length of 60 years, regardless of the site fertility and the interest rate used. On average, the lowest annual net $CO_2$ emissions were obtained on the OMT and MT sites with the rotation lengths of 80 and 100 years, respectively. However, when applying management including high pre-commercial stand density and fertilization, the difference was negligible between the rotation lengths of 60 and 80 years (Paper IV).

The positive effects of fertilization and higher pre-commercial stand density on both the production of stem wood and energy wood are also indicated by the negative $CO_2$ balance of forest ecosystem (carbon sink) and the net $CO_2$ emissions of the use of energy wood (Papers III-IV). The emissions were the highest, on average, without fertilization as related to lower growth. However, there were clear differences between Scots pine stands regarding the total stem wood production and the $CO_2$ emissions on the MT and VT sites, i.e. the productivity was clearly lower and $CO_2$ emissions higher (41%) on the VT sites. This was opposite to Norway spruce on the MT and OMT sites, but on the latter one the productivity was slightly higher.

In this work the increase of timber and energy biomass production by fertilization clearly decreased net $CO_2$ emissions in energy production. This is in line with the results of Sathre et al. (2010) and Eriksson et al. (2007), who found that the forest fertilization can significantly reduce the net GHG emissions and increase the availability of primary energy. According to the results of this work, the fertilization decreased the net $CO_2$ emissions for Norway spruce on the OMT and MT sites by 17 and 23%, respectively (compared to without fertilization). For Scots pine, the reduction was 12 and 19% on the MT and VT sites as related to the increased growth. Oren et al. (2001) have also emphasized the positive effects of nitrogen fertilization on the carbon sequestration of forest stands. This is in line with the results presented here. Over the life cycle, the net $CO_2$ emission per unit of energy were smaller for energy biomass than those for fossil fuels; i.e. the net emission was 65-152 kg $CO_2$ $MWh^{-1}$ for Norway spruce and 78-192 kg $CO_2$ $MWh^{-1}$ for Scots pine with the rotation length of 80 years. As a comparison, the corresponding $CO_2$ emission is 341 kg

$CO_2$ $MWh^{-1}$ for coal, if excluding emissions for the production and transportation (Statistics Finland 2005).

This work indicated that management had a clear effect on the mean C stock in the forest ecosystem. This was especially the case for the management regimes which allowed a higher tree stocking in the early phase of rotation than in basic management. The same regimes increased also the production of timber and energy wood. Thornley and Cannel (2000) and Garcia-Gonzalo et al. (2007) also earlier suggested that it might be possible to simultaneously increase the timber yield and the C storage in forests by maintaining the tree stocking higher throughout rotation compared to basic management. However, in general, the C stock is highest in the forest ecosystem if no thinning is applied over the rotation. The C stock depends also on the tree species, stand structure and properties of the site (Mäkipää et al. 1998, 1999, Pussinen et al. 2002).

In general, forest bio-energy supply chains seem to be effective in terms of energy input - output ratio. In earlier studies, the energy consumption was found to be 2-3% of produced energy and the $CO_2$ emissions were 4-7 kg $CO_2$ eqv$MWh_a^{-1}$, respectively (Wihersaari and Palosuo 2000, Wihersaari 2005). This held also for this study, i.e. the energy consumption varied in the range of 2-3% of that produced based on use of energy wood (Papers III-IV). Although, the consumption of energy in regard to harvesting, short- and long-distance transportation, chipping and fertilization depend on the management regime applied, the differences are small.

In addition to the use of proper management regimes over the rotation, also the use of the most productive genetic entries in regeneration may increase the potential of biomass recovery in integrated timber and energy wood production. This was found also in experimental data analyses of Norway spruce clones, i.e. large differences existed between clones in the dry mass production of stem wood and total above-ground production (Paper I). This is in line also with the results of Bujold et al. (1996), who suggested that such differences are typical for Norway spruce provenances. The variation in the total above-ground biomass of Norway spruce clones was, in this work (Paper I), related to the variation in the average proportion of stem wood (50-66%), branches (16-25%) and needles (17-26%). These results are in line with those by Johansson (1999), who found that in Norway spruces (about same age) the share of biomass was 15% for needles, 23% for branches and 62% for stem. On the other hand, the variability within the clones was large in this work, which probably could be related to the competition between neighboring trees.

The most productive clone (clone F430) in this work (Paper I) produced potentially up to 165 Mg $ha^{-1}$ in 28 years (6 Mg $ha^{-1}$ $a^{-1}$), if the planting density of 2500 trees $ha^{-1}$ was assumed. This is 71% above the average for all the clones included in the study, and it substantially exceeds the biomass yield of 43 Mg $ha^{-1}$ typically provided by Norway spruce in final fellings (Hakkila 2004). The clone F430 showed the largest above-ground growth both in terms of stem wood and crown mass. On the other hand, also the value of harvest index was high for this clone demonstrating large allocation of growth into stem. These properties also make the clone F430 a potential candidate for the combined production of timber and energy biomass. However, these findings are based on the stands with a mixture of clones, and it remains open whether this clone was as successful if grown alone in a pure stand. The preferences of clone mixtures in stands are recommended in order to reduce the risks related to pest and insect attacks and climatic variability (Roberds and Bishir 1997, Bishir and Roberds 1999). Currently, the use of clonal material is also expensive, and it will partly negate the economic profitability of the increased production, which the use of most productive clones might provide for biomass production.

To conclude, through proper forest management timber and energy wood production can be simultaneously increased and the net $CO_2$ emissions caused by energy wood use decreased. Increased forest growth, especially due to the fertilization and higher pre-commercial stand density in the early phase of stand development, induces most of the differences between management regimes regarding the net $CO_2$ emissions. It seems to be possible to produce forest biomass for energy purposes with relatively low $CO_2$ emissions by applying intensive management (especially frequent fertilization). This means that it may be valuable to evaluate the current fertilizing practices applied in Finnish forestry as nowadays fertilization is considered as most profitable in mature Norway spruce (MT sites) and Scots pine stands (VT sites) 10-15 years before final felling (Harstela 2004). In addition to fertilization, also successful regeneration (e.g. tree species/genetic entry and spacing) and suitable pre-commercial stand density and rotation length provide means to increase the production of timber and energy biomass and its profitability, but also means to increase carbon sequestration (and stocks) in forest ecosystem and decrease the $CO_2$ emissions caused by energy wood use. In the future, the effects of rotation length on timber and energy wood production and its profitability and $CO_2$ emissions in pure stands of Scots pine and proper management in mixtures of coniferous and broadleaves should be studied in greater detail, for example. The latter is because very often broadleaves are harvested in energy wood thinning in coniferous stands.

However, in the future studies the long-term effects of the nutrient removal in biomass harvest on the forest productivity and its environmental impacts should be assessed. This is necessary because there is evidence that the harvesting of logging residues increases the loss of nutrients, which may affect the long-term site productivity (Tamm 1969, Mälkönen 1976 , Jacobson et al. 2000, Nord-Larssen 2004). According to Jacobson et al. (2000), the whole-tree harvesting has reduced volume growth in both Scots pine and Norway spruce stands (5 and 6%) during the first 10 years after felling. On the other hand, the leaching of nutrients may also be a problem in fertilization. When compensating for the loss of nutrients in whole-tree harvest, the problem is probably the largest in the first years after fertilization (Saura et al. 1995). By using slow-release fertilizers, the environmental risks of nutrient leaching after fertilization are much lower than in the case of fast-release fertilizers (Saarsalmi and Mälkönen 2001).

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