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Impacts of initial stand density and thinning regimes on energy wood production and management-related CO_2 emissions in boreal ecosystems

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Abstract An ecosystem model (Sima) was utilised to investigate the impact of forest management (by changing both the initial stand density and basal area thinning thresholds from current recommendations) on energy wood production (at energy wood thinning and final felling) and management-related carbon dioxide (CO_2) emissions for the energy wood production in Finnish boreal conditions (62°39′ N, 29°37′ E). The simultaneous effects of energy wood, timber and C stocks in the forest ecosystem (live and dead biomass) were also assessed. The analyses were carried out at stand level during a rotation period of 80 years for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) growing in different fertility sites. Generally, the results showed that decreased basal area thinning thresholds, compared with current thinning, reduced energy wood (logging residues) and timber production, as well as carbon stocks in the forest ecosystem. Conversely, increased thinning thresholds increased energy wood production (ca. 1–27%) at both energy wood thinning and final felling and reduced CO_2 emissions (ca. 2–6%) related to the production chain (e.g. management operations), depending on the thinning threshold levels, initial stand density, species and site. Increased thinning thresholds also enhanced timber production and carbon stocks in the forest ecosystem. Additionally, increased initial stand density enhanced energy wood production for energy wood thinning for both species, but this reduced energy wood production at final felling for Scots pine and Norway spruce. This study concluded that increases in both initial stand density and thinning thresholds, compared with the current level, could be useful in energy wood, timber and carbon stocks enhancement, as well as reducing management-related CO_2 emissions for energy wood production. Only 2.4–3.3% of input of the produced energy (energy wood) was required during the whole production chain, depending on the management regime, species and sites. However, a comprehensive substitution analysis of wood-based energy, in respect to environmental benefits, would also require the inclusion of CO_2 emissions related to ecosystem processes (e.g. decomposition).

Keywords Ecosystem model · Emission calculation · Energy wood production · Management · Boreal ecosystem

Introduction

The growing concentration of atmospheric carbon dioxide (CO_2) and its contribution to global warming is a well-known phenomenon and long-term large-scale problem (IPCC 2007). Mitigation strategies to tackle this issue include reducing emissions and increasing the sequestration of carbon (C). With regards to these strategies, forests and forest management are receiving particular attention and can play a significant role in reducing net C emissions by capturing and storing of C in forest biomass and utilise them to substitute fossil fuels.

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In Finland (60–70° N, 19–32° E), the traditional way of managing forests has been to produce timber (pulpwood and sawlogs). Environmental concerns, responding to human-induced global warming, have lead to the realisation that the utilisation of other tangible and intangible forestry services must also be included as additional forest management objectives. Of them, the production of energy wood, as logging residues from final felling and small-sized trees from early thinning (energy wood thinning) or first commercial thinning for energy generation (Ahtikoski et al. 2008; Alam et al. 2010; Heikkilä et al. 2009; Hoen and Solberg 1994; Kärkkäinen et al. 2008) and exploring possibilities to enhance C capturing capacity in forest biomass and ecosystem (Alam et al. 2008, 2010; Briceño-Elizondo et al. 2006; Garcia-Gonzalo et al. 2007), is much highlighted at present.

The production of energy wood and harvested timber, and C in the growing stocks are affected by forest management practices (Alam et al. 2008; Heikkilä et al. 2009; Profft et al. 2009), i.e. the intensity and timing of thinning. Thinning of young stands yields wood suitable for pulp and energy (small-sized trees) and provides more growing space for the remaining trees, thereby shifts the distribution of growth to larger and more valued trees (e.g. Petritsch et al. 2007). During the later stages of stand development, pulpwood and sawlogs are produced, including energy wood from logging residues (i.e. the tree tops, branches and stumps) (Hall 2002).

Several previous studies have shown that leaving forests undisturbed or extending the rotation length could store more C in the forest ecosystem (Kaipainen et al. 2004; Karjalainen 1996; Liski et al. 2001; Pussinen et al. 2002). However, this would reduce the timber production suitable for industrial purposes (Alam et al. 2008; Seely et al. 2002). In order to find a solution on how the carbon stocks of forest ecosystem can be increased during a rotation period without losing forests' potential to produce timber, several efforts have been put on research. Some recent studies have explored the possibility of increasing both timber production and ecosystem carbon stocks by changing the stand management (Briceño-Elizondo et al. 2006; Garcia-Gonzalo et al. 2007; Alam et al. 2010). Changing management may also be used to increase the share of energy wood production together with timber as shown by Heikkilä et al. (2009). In this context, higher initial stand density might produce more energy wood during energy wood thinning and also at final felling (logging residues). In addition, increased basal area thinning thresholds could increase the production of energy wood, according to an earlier study conducted by the authors (Alam et al. 2010).

The use of wood-based energy is considered as a prospective substitute for fossil fuel. Energy wood use in lieu of fossil fuel has the advantage that could avoid C emissions related to fossil fuel burning. However, the use of various machines for forest management operations, extraction and transportation of wood requires fuel and emits CO_2 to the atmosphere, reducing partly the benefit of its utilisation (Schlamadinger et al. 1995; Yoshioka et al. 2005). Hence, computing CO_2 emissions from the energy wood production, apart from the emissions of energy wood combustion itself, requires considering the emissions related to forest operations and associated product transportation to the utilisation phase. From the forest management point of view, these emissions also vary depending on the utilised management operations and magnitude of management intensity (Eriksson et al. 2007).

Considering the above-mentioned issues, it is therefore necessary to evaluate the energy input and output associated with C accumulation in forests and release to the atmosphere, during the life cycle of forest production system. There has been some studies conducted using the life cycle approach for forest products emphasising mainly either on logging residues as by-product and/or alternative energy sources (Korpilahti 1998; Wihersaari 2005; Yoshioka et al. 2005) or on postharvesting wood products transportation and usage (Forsberg 2000; Gasol et al. 2009). There are gaps in knowledge in C emissions and energy used in whole management chain and operations (i.e. from the seedling production to the delivery of harvested wood to the manufacturing plants) for energy wood production when forest management is aimed to produce integrated energy wood and timber.

In this context, this study investigated the impacts of forest management (initial stand density and thinning regimes) on energy wood production (at energy wood thinning and final felling) and management-related CO_2 emissions for energy wood production in Finnish boreal conditions. The simultaneous effects of energy wood, timber and C stocks in the forest ecosystem were also assessed. The analyses were done at stand level during a rotation period of 80 years for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) growing in most-fertile, medium-fertile and less-fertile sites.

Materials and methods

Outlines of ecosystem model

This study utilised an ecosystem model (Sima) parameterised for the tree species growing between the latitudes N 60° and N 70° and longitudes E 20° and E 32° within Finland (Kellomäki et al. 1992, 2008; Kolström 1998). In the Sima model, the dynamics of the forest ecosystem is 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, regulated by the canopy gap dynamics of the tree stand. The model simulates the growth of individual tree and its component in a stand based on diameter. The model is run on an annual basis, and the computations are applied to an area of 100 m^2. The model is exhaustively described in several other papers (Kellomäki et al. 1992, 2008; Kellomäki and Kolström 1994; Kolström 1998), and therefore, only an outline of the model is presented here.

In this model, the growth and development of a tree in forest are determined by the incorporated four environmental subroutines (growth multipliers): temperature, light, soil moisture and decomposition. These subroutines determine the site conditions regarding temperature sum (degree days, +5°C threshold), within-stand light conditions, soil moisture and soil nitrogen. Thus, these factors directly affect the regeneration and growth of trees and indirectly influence the death of trees in tree populations and communities (Fig. 1). In the model, the probability of tree death at a certain moment increases with decreasing diameter growth due to crowding effect. Furthermore, the random mortality was included depending on maximum age of a tree (Kellomäki et al. 1992).

Temperature controls the geographical thresholds and annual growth response of each tree species and their ecotypes. Simultaneously, depending on the species and their height distributions, tree growth is controlled by competition for light. 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 drainage. The availability of nitrogen is controlled by the decomposition of litter and soil organic matter and is dependent on the quality of litter, soil organic matter and evapotranspiration.

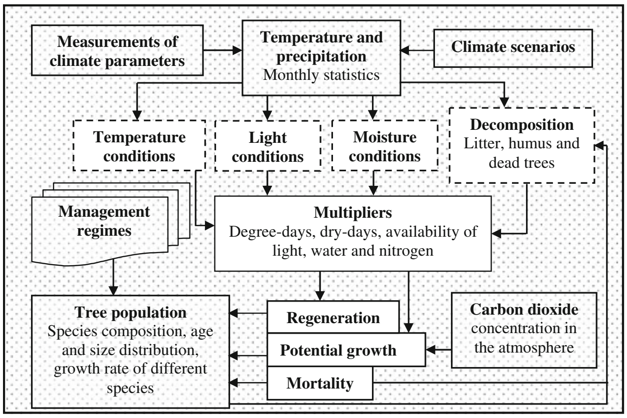


Fig. 1 Outline of the Sima model used in this study

The simulation of the above processes that take place in the forest ecosystem is based on the Monte Carlo simulation technique. That means certain events, such as the death of trees, are stochastic events. Whenever such a possibility happens, 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 of succession in the forest ecosystem must be repeated several times in order to determine the central tendency of variations over time (Bugmann et al. 1996). In this study, 400 replications of each scenario were conducted. The reported outputs were the mean values of these replications. The variability in output (e.g. basal area) among the repeated simulations within a scenario at different years of the rotation period was found to be less than 1% standard deviation from the mean value.

The validation of the Sima model has been previously discussed in detail in Kolström (1998) and Kellomäki et al. (2008), and the model has been found to be capable in predicting the development of boreal forest ecosystem. Furthermore, recently, Ruota et al. (2011) compared the growth of parallel simulations with the Sima model and the Motti model (Hynynen et al. 2002). The Motti model is a statistical growth and yield model in which tree growth estimation is based on data from a large number of forest inventory sample plots over the whole territory of Finland. This comparison (Ruota et al. 2011) showed that there is a fairly good correlation between the corresponding simulated values with the Motti and Sima simulators for different tree species. The Sima simulator seems slightly (10–20%) to underestimate the growth compared to the Motti simulator. Furthermore, the analysis in which the performance of the Sima model was analysed using data from 10 Forest Centres in southern Finland based on National Forest Inventory measurements (Peltola 2005) showed a close correlation between the measured and simulated growths (Routa et al. 2011).

Species, site types and forest management regimes

Scots pine and Norway spruce growing on different sites in eastern Finland (Joensuu region: 62°39′ N, 29°37′ E, 1,150–1,200 degree days) were simulated at a stand level during the whole rotation period (Fig. 2). The sites were *Oxalis-Myrtillus* (OMT) and *Myrtillus* (MT) for Norway spruce and *Myrtillus* and *Vaccinium* (VT) for Scots pine. The OMT, MT and VT represent most-fertile, medium-fertile and less-fertile sites, respectively (Cajander 1949).

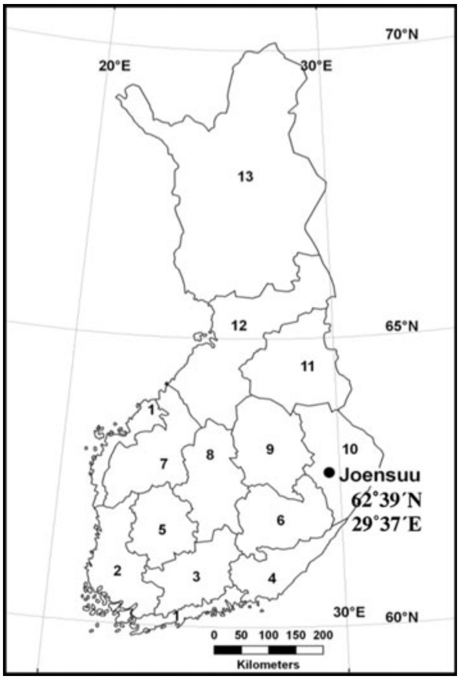


Fig. 2 Study area located in Joensuu region (*dot*) and forestry centres (*numbers*) in Finland

The selection of management regimes was made on the basis of preliminary analyses. Current thinning regime (Cu) followed the site- and species-specific thinning equal to those currently recommended in Finland (Tapio 2006). The basic idea of thinning recommendation is that whenever a given basal area threshold at a certain dominant height was reached, thinning was done (Fig. 3). Thinning was done from below and reduced the stocking to such a level that the remaining basal area was achieved to the desired value at a given dominant height (Tapio 2006). As recommended by Tapio (2006), energy wood thinning (EWT) was done a little earlier than the first thinning and EWT was done when a dominant tree height of between 8 and 14 m was reached. The remaining basal area threshold after EWT was also determined by following the site- and species-specific recommended number of trees. As recommended, first commercial thinning was executed when a tree dominant height of between 12 and 15 m was reached if EWT was not done. Final felling (FF) was done at the end of the 80-year rotation (Fig. 3).

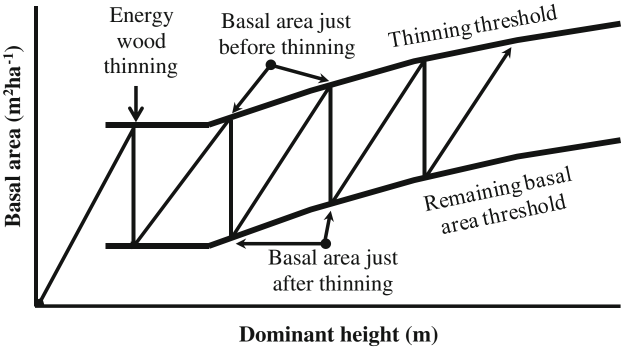


Fig. 3 Principles defining the thinning regime based on the development of dominant height and basal area as used in this study

The modified management regimes were constructed by means of changing both the basal area thresholds when the thinning is performed and the remaining basal area after the thinning, compared to Cu. (see Fig. 3; Table 1). In addition, initial stand density (ISD) was varied from 2,000 to 4,000 trees ha^{-1} (Table 1). Depending on the changes in basal area thinning thresholds and ISD, simulations were done for twenty-four management regimes for each species growing on each site type. Only timber (pulpwood and sawlogs) was produced in the traditional timber production

Table 1 Management regimes used in this study

Management regimes		Initial stand density, trees ha^{-1}	Energy wood production[a]	No. of thinnings
No changes in basal area thinning thresholds				
TP	Traditional timber production (0%)	2,000/ 3,000/ 4,000	No	2
Cu	Current thinning (0%)	2,000/ 3,000/ 4,000	Yes	2
% changes in basal area thinning thresholds from current recommendation				
M_1	Thinning thresholds increased by 10%	2,000/ 3,000/ 4,000	Yes	2
M_2	Thinning thresholds increased by 20%	2,000/ 3,000/ 4,000	Yes	2
M_3	Thinning thresholds increased by 30%	2,000/ 3,000/ 4,000	Yes	1/2[b]
M_4	Thinning thresholds reduced by 10%	2,000/ 3,000/ 4,000	Yes	3
M_5	Thinning thresholds reduced by 20%	2,000/ 3,000/ 4,000	Yes	3
M_6	Thinning thresholds reduced by 30%	2,000/ 3,000/ 4,000	Yes	3

Unchanged basal area thresholds (TP and Cu regime) correspond to the current thinning recommendations in Finland. Seedlings (2 cm dbh) were used as initial stand data in the simulation

[a] Energy wood was produced at energy wood thinning (small-sized trees) and final felling (logging residues)

[b] Norway spruce had one thinning and Scots pine had two thinnings in M_3

(TP) regimes. Besides timber production, the other regimes also included energy wood production in EWT (small-sized trees) and FF (logging residues). The thresholds for EWT were always similar for Cu and increased basal area thinning thresholds, but with decreased thinning thresholds, the species-specific stand density was decreased, though kept within the recommendation of Tapio (2006). As basal area and dominant height–based thinning thresholds were utilised in this study, the number of thinnings varied among the management regimes. This was because of the increase or decrease in thinning thresholds, which determined the thinning frequency for a specific management. For this reason, Cu, TP and increased basal area thinning threshold (M_1, M_2 and M_3) regimes had two thinnings, while decreased threshold (M_4, M_5 and M_6) regimes included three. The only exception was Norway spruce in M_3, where only one thinning was done regardless of ISD (Table 1).

Emissions calculation

We employed the management-related CO_2 emissions that are linked to the consumption of fossil fuel in the forest production system during the whole production chain (Kilpeläinen et al. 2011). The energy inputs required for each of the processes were analysed and calculated by multiplying 0.857 kg l^{-1} C content of fuel, to obtain kg CO_2 (C mass was converted into CO_2 mass) emissions for producing one unit of energy wood (MWh). Wood density of 400 kg m^{-3} was utilised in the calculation, while C content in dry biomass was assumed to be 50%. The functional unit for this study was determined as 1 ha of forest managed for 80 years. The system boundary includes seedling production and transportation, site preparation and planting, management operations (thinnings or harvesting), chipping and transportation of wood to the manufacturers' gate as well as all the related commuter traffic and transportation of machinery necessary to conduct the operations (Fig. 4).

The performance and consumption parameters of the machines used in the system were collected from available literature and summarised in Table 2. In the emission calculation, harvested energy wood and timber were transported an average distance of 70 km utilising 40 tonnes of transportation capacity. However, the truck load size was smaller, being 25 tons, for stump transportation. A constant coefficient of 0.70 was used for determining driving with an empty truck for the return trip. Energy wood chipping was done in the power plant yard by a drum chipper. In the system, average commuter traffic was assumed to be 50 km, and fuel consumption for a passenger car was 0.07 l km^{-1}. Average values for drum chipper and seedling transportation from nursery to the forests were assumed in this study. However, the emissions from the manufacturing and maintenance of the machines have not been included in the calculation.

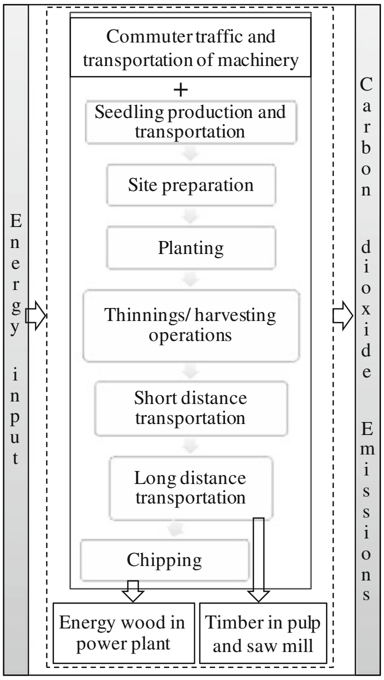


Fig. 4 Diagram of forest production system boundary

Calculation principles

In this study, an approach was used to integrate the simulation results obtained from an ecosystem model as an input for the emission calculation process. This enabled the inclusion of management operation emissions together with forest production system.

The forest growth refers to the mean annual increment of the growing stock (m^3 ha^{-1} $year^{-1}$). The estimated growth was based on the current climatic conditions. Based on diameter, the timber was sorted into sawlogs and pulpwood, with a minimum top diameter of 15 and 6 cm, respectively. In this study, bucking was not conducted based on the length of the stem. The timber was expressed as m^3 ha^{-1} $year^{-1}$. Other parts of the tree, such as, branches, tops of the stem, needles (loss in harvesting was assumed to be 30%), stumps and large roots, were considered as logging residues. Logging resides were collected only from FF. Apart from logging residues, energy wood (Mg ha^{-1}) also included small-sized trees from EWT. However, C stocks in the forest ecosystem (live and dead biomass) (Mg ha^{-1}) refer to the C in the stem, branches, leaves and roots in the growing stock and in the ground vegetation and forest floor including standing dead trees and are calculated as a mean annual accumulation over the rotation period.

The simulations enabled the calculation of the absolute values, over one rotation period, for the studied factors

Table 2 Parameters utilised in the calculation of forest production system in the emission calculation

Phases	Productivity	Fuel consumption
Forest establishment		
Seeding production		237.54 MJ $\text{seedling}^{-1000\text{a}}$
Seedling transportation (50 km)		0.40 l $\text{km}^{-1\text{b}}$
Site preparation	0.91 ha $\text{h}^{-1\text{c}}$	18.20 l $\text{h}^{-1\text{c}}$
Scarifier transportation	12.10 km $\text{ha}^{-1\text{d}}$	0.54 l $\text{km}^{-1\text{e}}$
Forest operations		
Thinning by harvester	8.20 m^3 $\text{h}^{-1\text{f}}$	12.00 l $\text{h}^{-1\text{f}}$
Final felling by harvester	17.20 m^3 $\text{h}^{-1\text{f}}$	12.00 l $\text{h}^{-1\text{f}}$
Stump removal (excavator)	13.00 m^3 $\text{h}^{-1\text{g}}$	15.00 l $\text{h}^{-1\text{h}}$
Forwarder and harvester transportation	0.16 km $\text{m}^{-3\text{i}}$	0.54 l $\text{km}^{-1\text{e}}$
Wood transportation and chipping		
Forwarding (thinning)	11.80 m^3 $\text{h}^{-1\text{f}}$	8.50 l $\text{h}^{-1\text{f}}$
Forwarding (final felling)	15.90 m^3 $\text{h}^{-1\text{f}}$	8.50 l $\text{h}^{-1\text{f}}$
Long distance transportation (truck)		
Transportation capacity: 40/25 tons		0.54 l $\text{km}^{-1\text{e}}$
Chipping (drum chipper)	150.00 m^3 $\text{h}^{-1\text{b}}$	60.00 l $\text{h}^{-1\text{b}}$
Commuter traffic (50 km)		0.07 l $\text{km}^{-1\text{b}}$

[a] Juntunen 1997, personal communication (Suonenjoki Research Station)

[b] Assumed in this study

[c] Berg and Karjalainen (2003) and Karjalainen and Asikainen (1996)

[d] Hämäläinen et al. (1992)

[e] Väkevä et al. (2004)

[f] Berg and Karjalainen (2003)

[g] Laitila et al. (2007)

[h] Karjalainen and Asikainen (1996)

[i] Kuitto et al. (1994)

(growth, energy wood, timber and C stocks) for all the management regimes. The results were compared to determine the effect of varying initial stand density and basal area thinning thresholds. Comparisons were always done with currently recommended management practice regardless of initial stand density and thinning thresholds.

Utilising simulation output and fuel consumption parameters from the literature, the CO_2 emissions of energy wood production from ‘cradle to gate’ were calculated for varying management regimes applied in this study. The unit was set as kg CO_2 MWh^{-1}.

Results

Effects of initial stand density (ISD)

Energy wood production

In Scots pine under 2,000 ISD, energy wood production at EWT and FF was about 6 and 52 Mg ha^{-1}, respectively, at the *Myrtillus* site over the 80-year rotation period. The production at the *Vaccinium* site corresponded to 5 and 49 Mg ha^{-1} (EWT and FF, respectively). Increased ISD compared with 2,000 ISD increased energy wood production at EWT at both the *Myrtillus* and *Vaccinium* sites (Fig. 5a, b). Increased ISD also enhanced energy wood production at FF at the *Myrtillus* site, but decreased it at the *Vaccinium* site. In Norway spruce, for both the *Oxalis-Myrtillus* and *Myrtillus* sites, the increasing pattern in energy wood production at EWT with increased ISD was similar to Scots pine growing in both sites. However, compared with 2,000 ISD, energy wood production at FF increased at the *Myrtillus* site only under 3,000 ISD (Fig. 5c, d).

Timber production and carbon (C) stocks

In Scots pine growing at the *Myrtillus* site, both 3,000 and 4,000 ISD increased timber production and C stocks in the ecosystem (live and dead biomass), compared to 2,000 ISD. However, in the case of the *Vaccinium* site, only 3,000 ISD increased timber production (Fig. 5a, b). In Norway spruce, compared to 2,000 ISD, increased ISDs (3,000 and 4,000) enhanced timber production at both the *Oxalis-Myrtillus* and *Myrtillus* sites, but only 3,000 ISD increased C stocks at the *Myrtillus* site (Fig. 5c, d).

Effect of varying basal area thinning thresholds under different initial stand density

Energy wood production

In general, under all ISDs (2,000–4,000 seedlings ha^{-1}), decreased basal area thinning thresholds, compared with current thinning regime (Cu), increased energy wood production at EWT (3–48%) though reduced it at FF (18–48%) for both Scots pine (*Myrtillus* and *Vaccinium*) and Norway spruce (*Myrtillus* and *Oxalis-Myrtillus*). Only M_4 management regime (10% decrease in thinning thresholds) reduced the energy wood production at EWT for Scots pine at the *Myrtillus* and *Vaccinium* sites corresponding to 2,000 and 3,000 ISD (see Fig. 6). Conversely, increased thinning thresholds, compared with Cu, affected energy wood production at EWT and FF in Scots pine mainly under 2,000 ISD at the *Myrtillus* site. In Norway

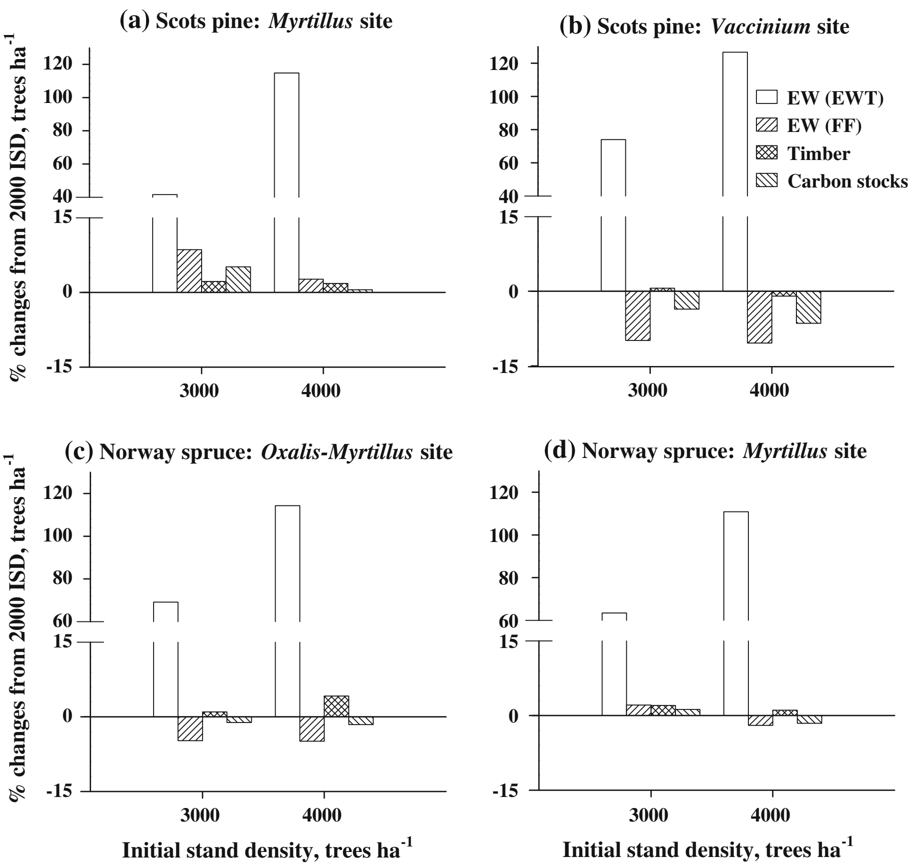


Fig. 5 Relative effects of initial stand density (ISD) taking 2,000 ISD, tree ha^{-1} as the baseline for energy wood production at energy wood thinning (EWT) and final felling (FF), timber production (sawlogs and pulpwood) and carbon (C) stocks in the forest ecosystem (live and dead biomass) for Scots pine at *Myrtillus* (**a**) and *Vaccinium* (**b**) sites and Norway spruce at *Myrtillus* (**c**) and *Oxalis-Myrtillus* (**d**) sites under current thinning regime (Cu)

spruce for all ISDs, increased thinning thresholds, compared with Cu, had little effect on energy wood production at EWT on both the *Oxalis-Myrtillus* and *Myrtillus* sites. Only the 30% increase in thinning thresholds (M_3 regime) enhanced energy wood production at FF (see Fig. 6).

Growth, timber production and C stocks

For both Scots pine and Norway spruce, changes in basal area thinning thresholds compared to Cu had a clear effect on growth, timber production and C stocks over the rotation. A decrease in thinning thresholds compared to Cu tended to decrease them for all ISDs (Fig. 7). Conversely, increased thinning thresholds enhanced growth and C stocks for both species, regardless of site type and ISD. Increased thinning thresholds also increased timber production for Scots pine at the *Myrtillus* site under 2,000 and 3,000 ISDs (Fig. 7). However, increased thinning thresholds did not affect the timber production for Scots pine in the *Vaccinium* site. Regarding Norway spruce, up to a 20% increase in the thinning thresholds increased the timber production, compared to Cu, only under 2,000 and 3,000 ISDs at the *Oxalis-Myrtillus* site. But a 30% increase in the thinning thresholds (M_3) increased the timber production for all ISDs at the *Myrtillus* site and 3,000 ISD at the *Oxalis-Myrtillus* site.

Compared to Cu, the traditional timber production regime (TP) generally reduced growth, timber production and C stocks for both Scots pine and Norway spruce. However, the TP regime increased growth and timber in Norway spruce at the *Myrtillus* and *Oxalis-Myrtillus* sites under 4,000 ISD, compared to Cu (Fig. 7). In Scots pine, TP regime increased growth, timber and C stocks in the *Vaccinium* site under 3,000 and 4,000 ISD, and only timber at the *Myrtillus* site under 4,000 ISD, compared to Cu (Fig. 7).

Energy wood production and related CO_2 emissions over the rotation period

Figures 8 and 9 show the effects of management regimes (varying basal area thinning thresholds and ISDs) on total energy wood production at both EWT and FF over the rotation period. Additionally, they show the emissions per energy wood production (kg CO_2 MWh^{-1}) for Scots pine at the *Myrtillus* and *Vaccinium* sites (Fig. 8) and Norway spruce growing at *Oxalis-Myrtillus* and *Myrtillus* sites (Fig. 9). Clearly, the energy wood production was higher and emissions per unit of energy were lower for Norway spruce than that for Scots pine. For both species, energy wood production was higher in more-fertile sites.

In Scots pine, for all ISDs, increased basal area thinning thresholds, compared to Cu, enhanced energy wood

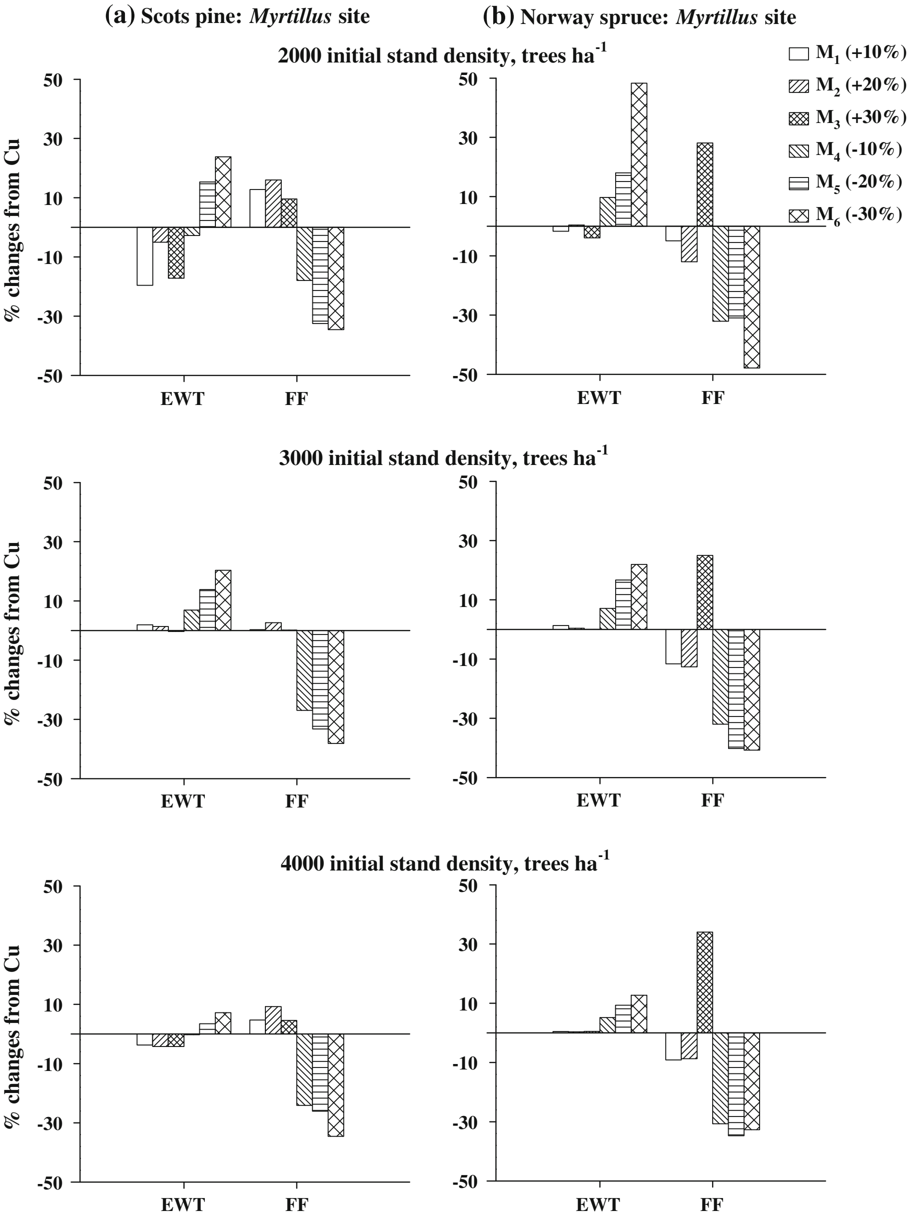


Fig. 6 Relative effects of varying basal area thinning thresholds taking the current thinning regime (Cu) as the baseline on energy wood production at energy wood thinning (EWT) and final felling (FF) for Scots pine (**a**) and Norway spruce (**b**) at *Myrtillus* site under varying initial stand density (ISD), tree ha^{-1}. See key to the management regimes in Table 1

production and decreased CO_2 emissions at the *Myrtillus* site (Fig. 8). The opposite results were found for decreased thinning thresholds for the same species at the same site. At the *Vaccinium* site, the increased thinning thresholds had a similar pattern to the *Myrtillus* site regarding energy wood production and CO_2 emissions, except for 2,000 ISD, where energy wood production was reduced slightly compared to the current thinning regime.

Decreased thinning thresholds compared with Cu affected Norway spruce at the *Oxalis-Myrtillus* and *Myrtillus* sites in a similar way to Scots pine, i.e. reduced energy wood production and increased emission to produce per unit of energy wood (Fig. 9). The only exception was found at the *Oxalis-Myrtillus* site with 2,000 ISD, where energy wood and CO_2 emissions were both lower. However, up to a 20% increase in basal area thinning thresholds, compared to Cu, did not show any major changes in energy wood and CO_2 emissions, but a 30% increase in thresholds enhanced the energy wood production and reduced CO_2 emissions for all sites and ISDs.

Discussion

The role of forests to produce energy wood and mitigate the climate change by substituting fossil energy may change objectives of forest management in the future. Current forest management practice aiming mainly at timber production may not necessarily be appropriate for the integrated production of energy wood and timber and

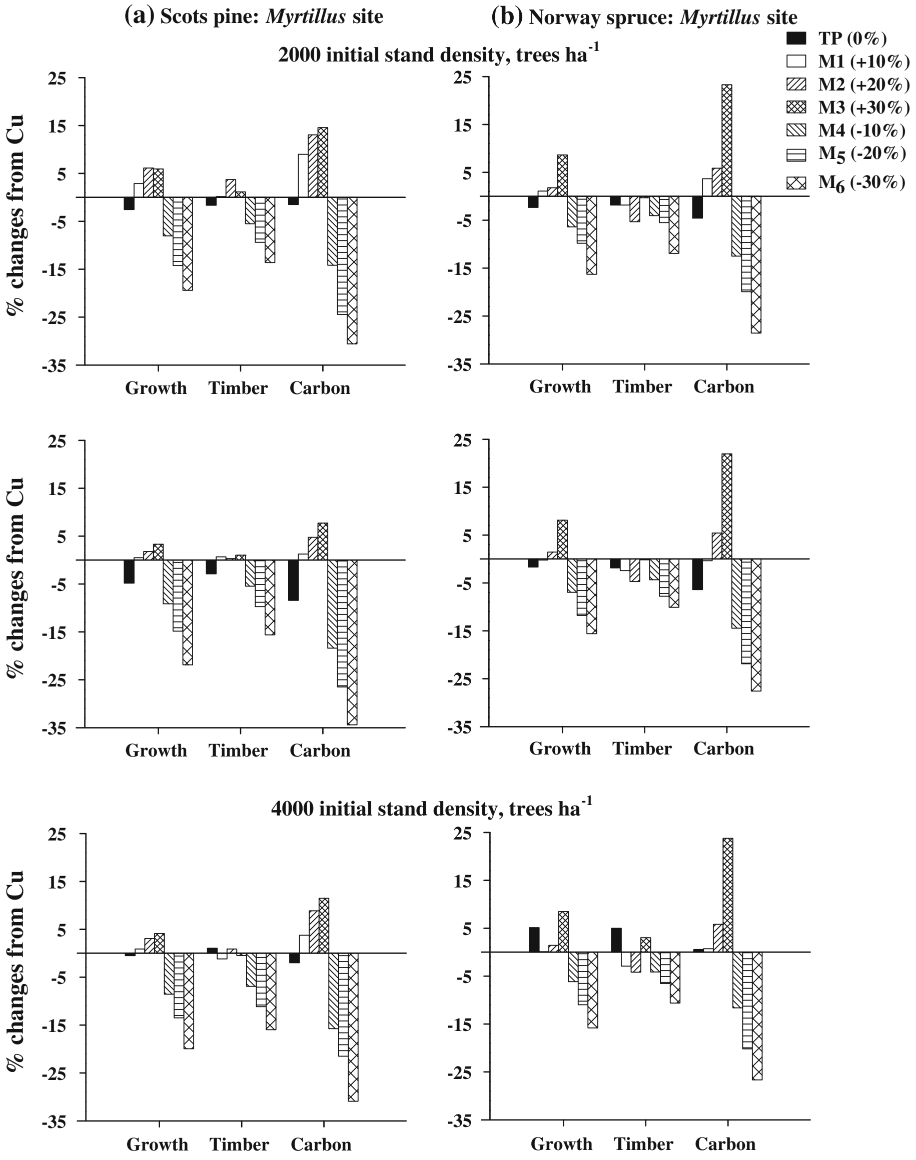


Fig. 7 Relative effects of varying basal area thinning thresholds taking the current thinning regime (Cu) as the baseline for growth, timber production and carbon (C) stocks in the forest ecosystem (live and dead biomass) for Scots pine (**a**) and Norway spruce (**b**) at the *Myrtillus* site under varying initial stand densities (ISDs), tree ha^{-1}. See key for the management regimes in Table 1

also for increasing the carbon sequestration and stocks in the forest ecosystem (live and dead biomass) in managed forest. Moreover, harvesting and transportation of forest biomass need inputs from fossil energy. In this context, this study investigated the impacts of varying management options (changes in ISD and basal area thinning thresholds compared with current recommendation) on energy wood production integrated with timber and C stocks during a rotation period of 80 years at the stand level in Finnish boreal conditions. An ecosystem model (Sima) was employed to simulate the above-studied factors, and thereafter, the results were utilised to calculate the CO_2 emissions from management operations for energy wood production. However, simulations did not include the specific effects of forest damages (e.g. wind throw, insect attack and forest fire) on the development of forests and tree stand.

The utilisation of energy wood is useful as it may reduce not only the dependency of imported fossil energy but also the emissions of CO_2 when it is a substitute for coal and oil. However, energy wood utilisation has also negative sides as the removal of organic matter and thereby nutrients could affect future forest growth (Jacobson et al. 2000). This concern partly makes harvesting of logging residues to be done at a smaller scale, although it has extensive growth potential in Nordic and Baltic countries (Alam et al. 2010, Hakkila 2004, Karjalainen et al. 2004). In Finland, energy wood (logging residues) harvesting is recommended to be done usually at more productive sites and that 30% of the removals should be left in the stand to ensure the nutrient cycle in the forest ecosystem (Äijälä et al. 2010). This is in line with the energy wood production of this study. Energy wood was harvested at EWT (small-sized trees) and FF (logging residues) for both

Fig. 8 Effect of management regimes on energy wood production (Mg ha^{-1}) and CO$_2$ emissions per MWh (kg CO$_2$ MWh^{-1}) for Scots pine at *Myrtillus* (**a**) and *Vaccinium* (**b**) sites between 2,000 and 4,000 initial stand density (ISD), tree ha^{-1}. See key to the management regimes in Table 1

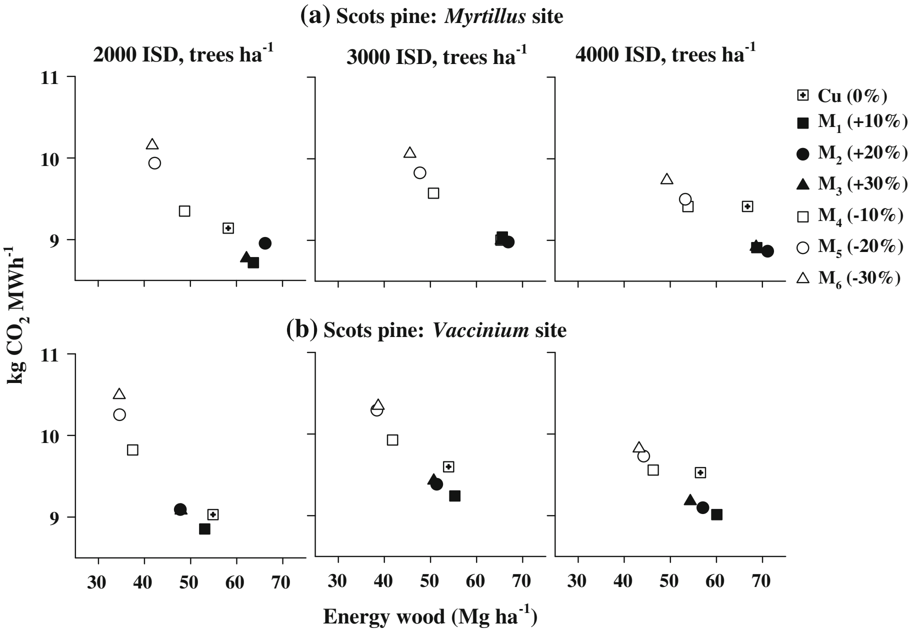
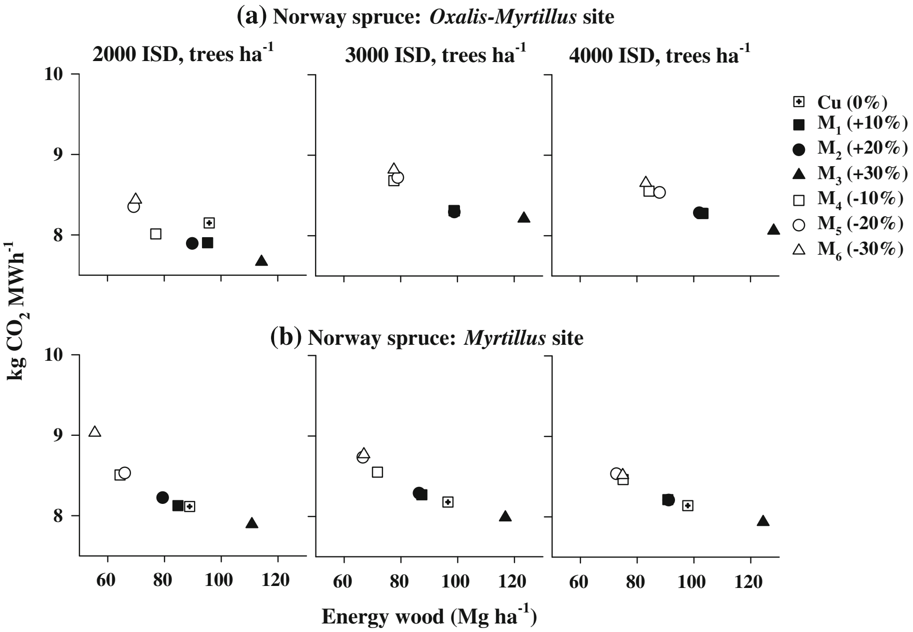


Fig. 9 Effect of management regimes on energy wood production (Mg ha^{-1}) and CO$_2$ emissions per MWh (kg CO$_2$ MWh^{-1}) for Norway spruce growing in the *Oxalis-Myrtillus* (**a**) and *Myrtillus* (**b**) sites between 2,000 and 4,000 initial stand density (ISD), tree ha^{-1}. See key for the management regimes in Table 1



Norway spruce and Scots pine. In general, a mature Norway spruce stand produces more logging residues than Scots pine owing to the larger share of crown mass (Hakkila 1991; Röser et al. 2008), which was also found in this study. However, the production of energy wood at EWT was found to be a similar value for both Norway spruce and Scots pine, which is in line with the findings of Heikkilä et al. (2009).

In this study, the number of thinnings varied among the management regimes owing to the utilisation of basal area and the dominant height–based cutting system adopted in Finnish forest management. The changes in thinning thresholds determine the thinning intensity in stands to be thinned. In general, increased thinning thresholds, compared to the current thinning regime, maintain higher tree stocking after thinning, resulting in a delay in successive thinnings due to the slower diameter growth. Thus, increased thinning thresholds may decrease the radial growth of individual trees, which leads to less harvestable timber (Mäkinen and Isomäki 2004a, b). This study also found that increased thinning thresholds enhanced concurrently energy wood production, growth and C stocks in the forest ecosystem, but did not affect timber production compared with the current thinning regime. On the other hand, decreased thinning thresholds, compared with current thinning, reduced C stocks in the forest ecosystem due to maintaining the decreased tree stocking over the rotation period. As decreased thinning thresholds had lower remaining basal area after EWT, compared with current thresholds, it increased energy wood production at EWT. The higher removal of energy wood at EWT reduced the timber production at successive cuttings and thus negatively impacted on the energy wood production at FF. In addition, decreased tree stocking enabled single tree volume to grow faster, thus increasing the number of thinnings over the rotation, implying less harvestable timber in each thinning as also found elsewhere (Briceño-Elizondo et al. 2006; Mäkinen and Isomäki 2004a, b; Thornley and Cannell 2000). As lower stocking levels may result in higher individual tree growth and vigour, it may potentially enabling greater resistance to environmental fluctuations and/or pest infestation (Röser et al. 2008).

Increased ISD, compared with 2,000 ISD, enhanced energy wood production at EWT, but at some sites, energy wood production at FF was reduced, for example, in Scots pine and Norway spruce in *Vaccinium* and *Oxalis-Myrtillus* sites, respectively. This was mainly caused by the fact that increased ISD means that EWT is likely to be done earlier, and therefore, subsequent thinnings were delayed, compared with 2,000 ISD due to not meeting the threshold of basal area and dominant height in thinning. Because of the delayed thinning, the time interval between last thinning and FF was shortened and, therefore, optimal growth potential remained unutilised during the later stages of the rotation period. A similar trend also held when both ISD and thinning thresholds were increased. This affected not only the energy wood production at FF but also timber production, as well as on-site C storage.

In previous studies, management implications for forest production have been identified, with attempts being made to compare the currently recommended management practice with changes either in basal area–based thinning levels (e.g. Alam et al. 2008; Briceño-Elizondo et al. 2006; Garcia-Gonzalo et al. 2007) or in rotation length (e.g. Kaipainen et al. 2004; Liski et al. 2001; Pohjola and Valsta 2007). Concurrently managing a forest for maximum carbon storage and energy wood production for fossil fuel substitution is challenging because these two represent competing demand (Kirschbaum 2003). This means that undisturbed forests store the most C, while utilisation of wood requires removal of wood from forests and reduce on-site C storage. However, Briceño-Elizondo et al. (2006) and Garcia-Gonzalo et al. (2007) reported that increased thinning thresholds compared with the current level could increase both timber production and on-site carbon storage. Increased timber production could also increase the energy wood production as reported by Maclaren (2000). However, these studies did not include the effects of changing ISD in the energy wood production. This study suggests that increases in both ISD and thinning thresholds compared with the current level could be an effective way to increase energy wood and timber production, as well as maintain higher C stocks in the ecosystem. In that case, rotation length would need to be extended compared to the one used in this study (Liski et al. 2001; Pohjola and Valsta 2007). Reduced rotation length could also be an option, but this could be applied only with decreased thinning thresholds (or tree stocking) compared to the current thinning level. This would decrease on-site carbon storage over the rotation, but increase the supply cycle of energy wood if forests are regenerated and managed in a sustainable way.

In this study, all the CO_2 emissions calculated for the forest establishment phase (seedling production and transportation, site preparation, transportation of scarifier and commuter traffic) were included in the energy wood production chain, and thus, the result could be an overestimation of the energy input required for energy wood production. However, this study showed that it was possible to concurrently enhance energy wood production and reduce management-related CO_2 emissions (kg CO_2 MWh^{-1}) if the ISD and the thinning thresholds are increased from the current practices. In general, the emissions per unit energy wood production of Norway spruce was lower than that of Scots pine, as can be expected owing to the former producing higher mass of logging residues though utilising similar amount of input energy. This study found that 2.4–3.3% input of the output energy is needed depending on the management regimes, sites and species. This means one unit of fossil energy could roughly produce 30–40 units of wood-based energy. Repo et al. (2010) reported also that management-related emissions were quite low compared to indirect emissions (decomposition of soil organic matter) from the forest ecosystems. In this study, the estimated emissions from the whole management chain for energy wood production were about 7.7–10.5 kg CO_2 MWh^{-1} depending on applied management, sites and species. This is in the range (4–20 kg CO_2 MWh^{-1}) reported by other studies (Korpilahti 1998; Mälkki and Virtanen 2003; Wihersaari 2005). The discrepancy might be due to the differences between the studies regarding the system boundary settings, selection of species and their growth potential, utilised site type, and assumed energy and moisture content in the wood.

Conclusions

This study concluded that energy wood production for Scots pine and Norway spruce can be enhanced by increasing both ISD and basal area thinning thresholds compared with the current forest management recommendation in Finland. At the same time, increased basal area thinning thresholds enhanced C stocks in the forest ecosystem for both species and timber production mainly in Scots pine. In addition, increased thinning thresholds reduced relative CO_2 emissions for the energy wood production. For a holistic approach, however, emissions related to ecosystem processes (e.g. decomposition) should also be included in the analysis when assessing the role of the forest in mitigating climate change. Effects of changing climate on growth of forest and decomposition of soil organic matter could also be considered in future modelling attempts. On the whole, climate change mitigation and emission reductions with the help of wood-based energy require also sustainable land use and forest management activities.

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