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Potential of forest biomass production and utilization for mitigation of climate change in boreal conditions

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Academic dissertation

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ABSTRACT

The aim of this work was to study the potential of forest biomass production and utilization for mitigating climate change in boreal conditions, based on integrated use of forest ecosystem model (SIMA) simulations and life cycle assessment (LCA). More specifically, it was studied how forest management (e.g. thinning regime, nitrogen fertilization, rotation length), harvesting intensity (timber, logging residues, stumps and coarse roots in the final felling) and gradually changing climate affect in Finnish conditions forest biomass production (timber and energy biomass) (Papers I, III, IV), carbon neutrality (Paper I) and net climate impacts of forest biomass production and utilization in substituting fossil-intensive materials and fuels (Paper III, IV). Furthermore, it was studied the need to adapt the cultivation of the main Finnish tree species under the gradually changing climate (Paper II).

This work showed that by modifying the business-as-usual (baseline) management and by increasing the harvesting intensity, we may increase simultaneously forest biomass production, carbon sequestration and stocks of forests, and climate benefits of forest biomass production and utilization. This could be done by maintaining higher stocking over a rotation (of 60 to 80 years) compared to the baseline management and using nitrogen fertilization, and harvesting in addition to timber, also logging residues, stumps and coarse roots for energy in the final felling. However, some trade-offs exist between the economic profitability of forest biomass production and climate impacts of forest biomass production and utilization. The impacts will also vary over time depending on the prevailing environmental conditions, forest structure and forest biomass assortments used in substitution. To conclude, gradual adaptation of forest management and utilization is needed in the future, taking into account the prevailing environmental conditions (climate, site) and uncertainties related to the climate change, to fully utilize the positive effects of climate change and reduce the negative ones.

Keywords: forest management, climate change, forest biomass production, substitution, climate impact, boreal forests

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Joensuu, May 2015

Piritta Torssonen

LIST OF ORIGINAL ARTICLES

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

I Pyörälä P., Peltola H., Strandman H., Kilpeläinen A., Asikainen A., Jylhä K., Kellomäki S. (2014). Effects of management on economic profitability of forest biomass production and carbon neutrality of bioenergy use in Norway spruce stands under the changing climate. Bioenergy Research 7: 279-294. http://dx.doi: 10.1007/s12155-013-9372-x

II Torssonen P., Strandman H., Kellomäki S., Kilpeläinen A., Jylhä K., Asikainen A., Peltola H. (2015). Do we need to adapt cultivation of main boreal tree species under the projected changing climate? (Manuscript in evaluation process)

III Torssonen P., Kilpeläinen A., Strandman H., Kellomäki S., Asikainen A., Jylhä K., Peltola H. (2015). Effects of climate change and management on net climate impacts of production and utilization of energy biomass in Norway spruce with stable age-class distribution. Global Change Biology Bioenergy. http://dx.doi: 10.1111/gcbb.12258

IV Kilpeläinen A., Torssonen P., Strandman H., Kellomäki S., Asikainen A., Peltola H. (2015). Net climate impacts of forest biomass production and utilization in managed boreal forests. Global Change Biology Bioenergy. http://dx.doi: 10.1111/gcbb.12243

Piritta Torssonen (née Pyörälä) was the main author for Papers I-III and had the main responsibility for all model based analysis and writing of Papers. She also performed all data analysis for Paper IV, but the writing of Paper was done together with the co-authors. The co-authors of different Papers have improved the work by commenting on the manuscripts.

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LIST OF DEFINITIONS AND ABBREVATIONS

CO_2	Carbon dioxide
GHG	Greenhouse gas
LCA	Life cycle assessment
LU, LULUCF	Land use, Land-use change and forestry
N	Nitrogen
NPV	Net present value
Carbon neutrality (CN)	Ratio between the net reduction/increase of direct CO_2 emissions in the bioenergy system (i.e. the simulation case) and the CO_2 emissions of the reference energy system over a given period of time.
Carbon stock of forest ecosystem	Amount of carbon in the forest ecosystem in trees and soil (humus and litter) over a given time period.
Forest biomass	Biomass in living trees, including foliage, branches, stems, coarse roots and fine roots.
Energy biomass	Energy wood from energy wood thinning and harvest residues (the top parts of stems, foliage and branches) and stumps and coarse roots from final felling.
Net ecosystem CO_2 exchange (NEE)	Balance between carbon bound in biomass growth (C_{seq}) and CO_2 emissions from the decomposition of soil organic matter (humus and litter) (C_{decomp}).
Net CO_2 exchange (C_{net})	Balance between the carbon uptake due to growth (C_{seq}), CO_2 emissions from decomposition of soil organic matter (C_{decomp}) and management (C_{man}), and combustion of energy biomass (C_{harv}).
Net climate impact (I)	I is a difference in the net CO_2 exchanges between the selected management scenario (I_{BIO}) and the reference scenario (I_{REF}).
Radiative forcing (RF)	Change in the net energy balance of the Earth system as affected by increase/decrease of CO_2 level in the atmosphere.
Timber	Stem wood fulfilling dimensions of saw logs and pulp wood.

1 INTRODUCTION

1.1 Background of the study

One of the main priorities of global environmental policy is the mitigation of climate change, which is denoted by the reduction of sources or enhancing the sinks of greenhouse gases (GHG) by anthropogenic interventions (IPCC 2001). In this respect, forests and forestry can provide several ways to mitigate climate change, including reducing deforestation, increasing afforestation, increasing the carbon density of existing forests through reforestation and proper management, and substituting fossil-intensive materials and fuels by forest biomass (Canadell and Raupach 2008; Malmsheimer et al. 2011).

Global climate is expected to warm substantially by 2100, especially due to the increase in the atmospheric carbon dioxide (CO_2) concentration. In Finland, the foreseen climate change is projected to increase the mean annual temperature by 3–6°C and precipitation by 11–18% by 2100, depending on the scenario used for the GHG concentrations (IPCC 2013). The concurrent elevation of mean annual temperature and atmospheric CO_2, together with changes in precipitation, is expected to greatly affect the functioning and dynamics of boreal forests as well as the biomass production and carbon sequestration of forest ecosystems (Garcia-Gonzalo et al. 2007a, b; Kellomäki et al. 2008; Poudel et al. 2011, 2012). This is because currently growth and dynamics of boreal forests are mainly limited by short growing period, relatively low summer temperatures and availability of nitrogen (Tamm 1991). However, forest management and environmental conditions (prevailing climate and site) also affect biomass production and carbon sequestration of forest ecosystems (Liski et al. 2001; Briceno-Elizondo et al. 2006; Matala et al. 2006, 2009; Garcia-Gonzalo et al. 2007a, 2007b).

In general, climate change is expected to increase biomass production in boreal forests of Fennoscandia (Bergh et al. 2003; Briceño-Elizondo et al. 2006). However, the sensitivity of different tree species to climate change, climatic variability and weather extremes like droughts may differ depending on region and prevailing climatic conditions (Kellomäki et al. 2008; Ge et al. 2013a, 2013b; Granda et al. 2013). Thus, proper site-specific cultivation of different tree species should be emphasized in the future to ensure sufficient water and nutrient availability for tree growth under the changing growing conditions (Kolström et al. 2011).

In Nordic countries, because forest management is generally done at stand level, forests constitute mosaics of single stands of varying site fertility, tree species composition, age structure and volume of growing stock. To obtain a long-term sustainable flow of timber from the forest region an even age-class distribution of forest has been a long-term target in forest policy. The current and future structure and functioning of forests and their consequent mitigation and adaptation potential are also largely dependent on the timing and intensity of management and harvesting (Sathre et al 2010; Poudel et al. 2011, 2012). In general, the net ecosystem CO_2 exchange is at its highest at the younger stand age and starts to saturate after an intermediate age, affecting the average carbon stock and biomass production over rotation (Liski et al. 2001; Hyvönen et al. 2007). The mean annual carbon stock and carbon sequestration of forests may be increased over a rotation by maintaining a higher stocking, which results in a lower harvesting frequency than in the business-as-usual management (Garcia-Gonzalo et al. 2007a, 2007b; Nunery and Keeton 2010; Alam et al. 2012). In boreal forests especially in northern Europe, the addition of nitrogen will enhance the growth of trees, as well as the litter fall onto the soil and the amount of carbon in the humus layer and mineral soil (Mäkipää 1995; Hyvönen et al. 2007, 2008). However, the growth response of trees to nitrogen fertilization depends on the tree species, developmental phase of the growing stock, site fertility and the dose of the added nitrogen (Bergh et al. 2014).

In Finland, the annual increment of growing stock has been higher than the annual drain for many decades. The total roundwood consumption was 73.9 million m^3 in 2013, of which 26.2 million m^3 was used by wood-products industries and 38.3 million m^3 by pulp industries (Finnish Statistical Yearbook of Forestry 2014). About 25% (341 PJ) of the current energy consumption in Finland consists of wood-based energy. The main components of energy biomass are by-products and wood residues (e.g. bark and black liquor) from sawmilling and chemical pulp industry (Finnish Statistical Yearbook of Forestry 2013). The use of residual forest biomass in energy production increased rapidly in the 2000s from less than one million m^3 to almost 9 million m^3 annually (Torvelainen et al. 2014). Recently, the Finnish national renewable energy action plan has set a 2020 target of 25 TWh for the use of forest chips in the generation of power and heat (National Energy and Climate Strategy, 2013).

Until recently, bioenergy was considered to be carbon neutral since the emissions would eventually be sequestered in the future growth of forests. However, this assumption has been questioned due to the time difference between biomass combustion and regrowth, and the decrease of carbon stock and carbon sink capacity of forest (e.g. Searchinger et al. 2008; Cherubini et al. 2009; Melillo et al. 2009; Melin et al. 2010; Repo et al. 2011, 2012, 2014; Zanchi et al. 2012; Buchholz et al. 2015).

In boreal conditions, forest management is characterized by a long production cycle from regeneration to final harvest. In this sense, compared to experimental studies, simulations by forest ecosystem models offer a means to study the sensitivity of the growth and dynamics of forests to management regimes (e.g. thinning and nitrogen fertilization regime, and rotation length) under varying environmental (climate, site) conditions. By combining forest ecosystem modelling with life cycle assessment (LCA), the impact of forest management on CO_2 emissions from forest biomass production and utilization can also be assessed (Sathre et al. 2010; Kilpeläinen et al. 2011; Poudel et al. 2011, 2012).

Although, there are a large variety of LCA studies related to the forestry sector and forest biomass production and utilization (Buchholz et al. 2015; Klein et al. 2015), two different approaches can be distinguished; i.e. attributional and consequential LCA (e.g. Curran et al. 2005; Brander et al. 2009). The attributional LCA approach assesses the system ‘as it is’, taking into account the direct effects at a given point of time (Brander et al. 2009; Helin et al. 2013). In consequential LCA, the impacts of decisions made from a selected time point onwards are studied, answering the question of how flows will change in response to any particular actions (Curran et al. 2005; Kilpeläinen et al. 2012). The consequential LCA approach is commonly used to compare both renewable and fossil systems side by side in order to consider the direct and indirect effects (Brander et al. 2009; Cherubini et al. 2011). When the effects of the use of forest-based bioenergy are compared to variable fossil fuels, the results also vary according to the carbon and energy content of the substituted material (Gustavsson et al. 2015). Furthermore, definition of the spatial system boundaries is important due to differences in carbon dynamics of the stand and landscape level.

It is also crucial to understand the time-dependencies of the carbon fluxes through emissions release and carbon sequestration as well as the atmospheric residence times of carbon (Sathre and Gustavsson, 2011, 2012; Ter-Mikaelian et al. 2011; Mitchell et al. 2012; Helin et al. 2013; Kurtz et al. 2014; Gustavsson et al. 2015). To integrate emissions over the time and consider the climate impacts of all the forest functions simultaneously, one option is to follow the annual carbon flows and carbon stocks both in the forest ecosystems and the consequent technosystem. Furthermore, a reference situation should consider alternative land use (e.g. baseline management) when comparing the implications of the use of different management scenarios over time (Helin et al. 2013; Lamers and Junginger 2013; Ter-Mikaelian et al. 2015). In LCA, the global warming potential (GWP) is commonly used in climate impact analysis to show the dynamics of GHG emissions in relation to CO_2 equivalents within fixed time frames (Helin et al. 2013). However, a fixed time frame leads to loss of temporal dimensions, and thus does not provide the dynamics of the greenhouse impact (Foster et al. 2007; Kirkinen et al. 2008). Temporally, the release of carbon into the atmosphere varies from almost immediate release (combustion of energy biomass) to, for instance, prolonged release over decades or centuries (panels, log houses). Recently, the potential climate impacts of forest-based bioenergy with respect to climate change mitigation has been studied widely by employing the metrics of radiative forcing (the balance of the Earth's radiation) (Kirkinen et al. 2008; Repo et al. 2011, 2012, 2014; Sathre and Gustavsson 2011, 2012; Kilpeläinen et al. 2012; Cherubini et al. 2013), which takes into account the time-dependences of GHG fluxes and the atmospheric residence times of GHGs.

1.2 Aim of the study

The main aim of this work was to study the potential of forest biomass production and utilization for mitigating climate change in boreal conditions by employing forest ecosystem model (SIMA) simulations and life cycle assessment (LCA) (Fig. 1). More specifically, in Papers I-IV it was studied:

(i) The effects of forest management on the economic profitability of forest biomass production and carbon neutrality of energy biomass utilization in Norway spruce (*Picea abies* L. Karst) stands under the changing climate (Paper I).

(ii) The need to adapt the cultivation of the main Finnish tree species of Norway spruce, Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth) under the projected climate change, considering also the uncertainties related to the climate change (Paper II).

(iii) The effects of forest management and climate change on the net climate impact of the production and utilization of energy biomass in Norway spruce forest with a stable age-class distribution (Paper III).

(iv) The net climate impact of forest biomass production and its utilization as a substitute for fossil-intensive materials and fuels in managed boreal forests (Paper IV).

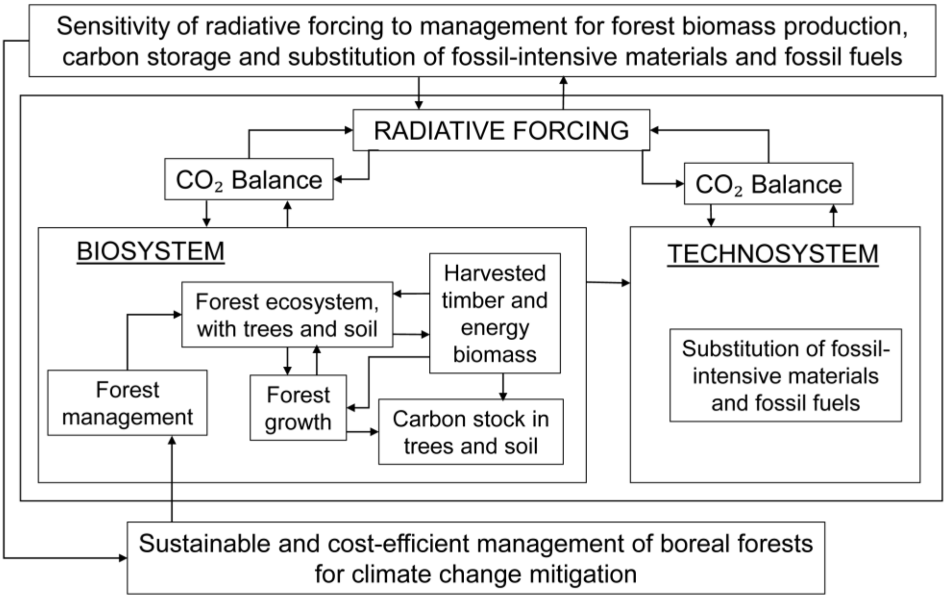

Figure 1 Outlines of the work.

2 MATERIALS AND METHODS

2.1 Outlines of the model approaches

A well-validated gap-type forest ecosystem model (SIMA) (Kellomäki et al. 1992, 2005, 2008) was used to simulate the growth and development of boreal forests throughout Finland, as affected by the temperature conditions, availability of light, soil water and nitrogen, and CO_2 concentration in the atmosphere. The risk of dying is determined by the competition between trees for resources reducing growth in a given year. Furthermore, trees may die randomly. Organic matter in litter and dead trees ends up in the soil, where its decay releases carbon dioxide and nitrogen. The dynamics of the available nitrogen are determined by the amount of nitrogen released and immobilized by the decomposition of soil organic matter. The management controls the dynamics of ecosystem, including regeneration (the planting of given species at a desired spacing), thinning from below, nitrogen fertilization and final felling. For the harvesting, both timber (saw logs and pulp wood) and energy biomass can be considered. Timber is sorted based on the following top diameter limits: 17 cm for saw logs and 6.5 cm for pulp wood. Energy biomass includes energy wood from energy wood thinning, and harvest residues (the top parts of stems with a diameter of less than 6.5 cm, foliage and branches) and stumps and coarse roots from final felling.

The life cycle assessment tool utilizes the simulation outputs of SIMA model to estimate the annual net CO_2 exchange (C_{net}) (Papers I, III–IV) (Kilpeläinen et al. 2011). The calculations of C_{net} are done on an annual basis (g CO_2 m^{-2} a^{-1}) by summing the carbon uptake due to growth (C_{seq}) and CO_2 emissions from decaying soil organic matter and management (C_{decomp}, C_{man}), and the combustion of energy biomass (C_{harv}).

2.2 Model based simulations

In Paper I, the effects of forest management and climate change on the economic profitability of forest biomass production (timber and energy biomass) and carbon neutrality of energy biomass utilization in Norway spruce were studied based on stand level analysis (Table 1). Simulations were carried out in central Finland, Joensuu region (62°40' N, 29°38' E) using as a baseline the current business-as-usual forest management in Finland (Äijälä et al. 2010, 2014). Management was also varied so that a higher stocking than that of the baseline management was maintained over the simulation period and nitrogen fertilization applied, respectively. The length of the simulation period varied from 30 to 80 years with 10-year intervals.

In Paper II, the possible need to adapt the cultivation of the main Finnish boreal tree species was studied, also taking into account the uncertainties related to projected climate change. In this study, the annual growth of stem wood in young Norway spruce, Scots pine and silver birch stands were simulated for different site fertility types and temperature gradients throughout Finland (60–70° N) under the changing climate (for the period 2010–2099). The currently recommended planting densities for Norway spruce, Scots pine and silver birch were used to initialize the simulations (Table 1). No management was applied over the 30-year simulation periods.

In Paper III, the effects of forest management and climate change on the net climate impacts of the production and utilization of energy biomass were studied in Norway spruce forest with a stable age-class distribution in central Finland, Joensuu region (Table 1). Data used for the analysis consisted of 80 single Norway spruce stands (1 ha) with an 80-year simulation time to mimic a stable age-class distributed forest area, where clear cutting was done annually for the oldest stand and after clear cutting the stand was regenerated and managed following the same management regime. The current business-as-usual Finnish forest management was used as a baseline management regime (Äijälä et al. 2010, 2014). Management was also varied so that a higher stocking than that of the baseline management was maintained over the simulation period and nitrogen fertilization applied, respectively.

In Paper IV, the net climate impacts of forest biomass production and its utilization were studied (Table 1). In the simulations, as inputs it was used site fertility and sample tree data available for subsample plots in the 9th National Forest Inventory of upland mineral sites throughout Finland (covering ca. 17 million ha of forest land). The current Finnish forest management was used as a baseline management regime (Äijälä et al. 2010, 2014). Management was also varied so that a higher/lower stocking was maintained over the simulation period compared to the baseline management.

Table 1 Simulations in Papers I-IV.

Inputs	Paper I	Paper II	Paper III	Paper IV
Tree species (Planting density, trees ha^{-1})	Norway spruce (2 500)	Norway spruce (2000), Scots pine (2000), silver birch (1600)	Norway spruce (2 500)	Norway spruce (2500), Scots pine (2500), silver birch (1600)
Initial breast height diameter, cm	2.5	2.5	2.5	2.5
Simulation area	Central Finland, 62°40' N, 29°38' E	Finland, 60° – 70° N	Central Finland, 62°40' N, 29°38' E	Finland, 60° – 70° N
Site fertility type	Moist / moderately-rich sites	From dryish to moderately-rich sites	Moist site	All site fertility types
Climate	Current; SRES A2	Current; SRES B1, A1B and A2	Current; SRES B1 and A2	Current
Simulation time, years	30, 40, 50, 60, 70 and 80	3 × 30-year periods	80	90
Change in stocking, %	+20 and +30	-	+20	±20
Nitrogen fertilization, kg N ha^{-1}	1-2 x 150	-	2 x 150	-
Timber and energy biomass harvest	Saw logs and pulp wood in thinnings and final felling; Harvest residues / stumps, coarse roots from final felling	-	Same as in Paper I	Otherwise same as in Paper I, but also energy wood thinning done

In the simulations, the current climate data were based on measurements of temperature and precipitation by the Finnish Meteorological Institute (FMI) during the reference period 1971–2000. The current climate data were interpolated onto a 10 km × 10 km grid based on mean monthly values (Venäläinen et al. 2005; Aalto et al. 2012). The changing climate was provided by the ACCLIM Project (Jylhä et al. 2009) and interpolated onto a 50 km × 50 km grid throughout Finland. The closest grid point to each forest inventory plot was used in the simulations under the current climate and climate change scenarios. The climate change projections were derived from nineteen global climate model simulations originating from the CMIP3 multimodel data set (Meehl et al. 2007). The projections depict the multimodel mean climate change during this century under the SRES B1, A1B and A2 emissions scenarios (Nakićenović et al. 2000). The elevation of atmospheric CO_2, mean annual temperature and precipitation changes observed for the SRES B1 (the CMIP3 climate projection) correspond to the RCP4.5 of the new CMIP5 database (Taylor et al. 2012).

Whereas, the SRES A2 shows a 1.3–1.5 °C smaller temperature increase in summer from southern to northern Finland compared to the RCP8.5.

2.3 Analysis of simulation outputs

The effects of forest management and climate change on the economic profitability of forest biomass production (timber and energy biomass) were calculated based on the net present value (NPV with a 3% interest rate) (Papers I, III and IV; see Table 2). In order to study the possible need to adapt the cultivation of the main Finnish tree species, the growth of stem wood in young stands was studied under the gradually changing climate for different site fertility types, temperature gradients and time spans (Paper II, see Table 2). Furthermore, the effects of management and climate change on the carbon stock in the forest ecosystem (including carbon in trees and soil – humus and litter) and the net ecosystem CO_2 exchange (NEE) (Table 2) were analysed. The net ecosystem CO_2 exchange was considered as a balance between carbon bound in biomass growth and CO_2 emissions from the decomposition of soil organic matter (humus and litter). The carbon neutrality (CN) of energy biomass production in Norway spruce and its use in energy production was approached via the carbon neutrality concept by Schlamadinger et al. (1995). This indicates the ratio between the net reduction/increase of direct CO_2 emissions in the bioenergy system (i.e. the simulation case study) and the CO_2 emissions from the substituted energy from the reference energy system over a given period of time. The specific CO_2 emissions per unit of energy produced over the rotation were used to analyse the carbon neutrality of energy biomass use for certain management regimes (Paper I).

Table 2 Analyzed variables in different papers.

Variables	Units	Papers
Timber and energy biomass production	m^3 ha^{-1} a^{-1}; Mg ha^{-1} a^{-1}; Tg C a^{-1}	I, III, IV
Net present value	€ ha^{-1} a^{-1} (3 % interest rate)	I, III
Net ecosystem CO_2 exchange (NEE)	g CO_2 m^{-2} a^{-1}	I, III, IV
Net CO_2 exchange of forest biomass production and utilization (C_{net})	g CO_2 m^{-2} a^{-1}	I, III, IV
Carbon neutrality (CN)	-	I
Radiative forcing (RF)	W m^{-2}	III, IV
Total growth of stem wood, total stem volume and mortality of trees	m^3 ha^{-1}; number of trees ha^{-1}	II

In Papers III and IV, the net climate impact of forest biomass production and its utilization as a substitute for fossil intensive materials and fuels were calculated. Net climate impact (I) refers to the change in radiative forcing (RF, W m^{-2}), quantifying the impact on the atmosphere caused by CO_2 emissions resulting from the production and utilization of forest biomass (Eq. 1) (Ramaswamy et al. 2001). In this context, the production system based on the use of forest biomass to produce materials and energy for the manufacturing and energy sectors is named as "biosystem". Similarly, the production system producing fossil-intensive materials (e.g. concrete and plastic) and energy by using fossil fuels (coal, oil) is named as "fossil system". In this regard, net climate impacts (I) were calculated by Eq. 1:

$$\mathrm{I} = \mathrm{I}_{\mathrm{BIO}} - \mathrm{I}_{\mathrm{REF}} \quad (1)$$

where I_{BIO} refers to the climate impacts of the alternative management regime (C_{net}) and I_{REF} to the climate impacts of the baseline management regime without harvesting energy biomass, but with the use of fossil-intensive materials and fuels.

3 RESULTS

3.1 Forest biomass production and its economic profitability

Both at stand (Paper I) and regional (Paper III) level, by maintaining stocking 20 and 30% higher compared to the baseline management and by simultaneously applying nitrogen (N) fertilization, or by using N fertilization alone, the mean annual timber production of Norway spruce could be increased by up to 10%, regardless of rotation length, site fertility type and climatic conditions. However, the baseline management with and without nitrogen fertilization resulted in the highest net present value (NPV) for longer rotations (60 to 80 years) (Papers I, III).

Based on national level analysis (Paper IV), the maintenance of lower stocking (−20%) led to a higher mean annual timber production in the short-term compared to the maintenance of higher stocking (+20%) with later thinnings. However, in comparison to the baseline management, the maintenance of lower stocking (−20%) led to a higher yield of pulp wood, but had only a minor effect on the yield of saw logs. Maintenance of 20–30 % higher stocking increased also the mean annual harvest of energy biomass compared to the baseline management and/or use of nitrogen fertilization (Papers I, III–IV). The mean annual energy biomass harvest was on average higher for shorter rotations (30 to 50 years) than for longer rotations (Paper I).

As a result of climate change (SRES A2), both at the stand and regional level the mean annual production of timber decreased in the managed Norway spruce stands in central Finland (Joensuu region) (Papers I and III). In Paper II, the simulations throughout Finland showed that the growth of young Norway spruce stands were clearly lower in southern and central Finland under moderate and strong climate change (A1B and A2) compared to the current climate. The growth reduction under the A1B and A2 was the largest on the less fertile sites, with the highest number of drought extremes and greatest mortality. Opposite to Norway spruce, the growth of young Scots pine and silver birch increased under the changing climate and the most under strong climate change (A2) (Paper II). The increase was also higher on fertile sites than on less fertile sites throughout Finland. In northern Finland, the growth of Norway spruce was clearly higher under the changing climate than under the current climate, similar to Scots pine and silver birch, and regardless of site fertility type, climate change scenario and time span.

3.2 Net climate impacts of forest biomass production and utilization

Both at stand (Paper I) and regional (Paper III) level, the highest carbon stock in the forest ecosystem was obtained by maintaining higher stocking (+20, +30 %) compared to the baseline management and by applying 60- to 80-year rotation lengths with or without N fertilization. These management regimes also gave the highest net ecosystem CO_2 exchange (Papers III and IV) and net CO_2 exchange (Paper I). The net ecosystem CO_2 exchange was also improved by harvesting stumps and coarse roots in addition to logging residues. However, this led to a somewhat lower carbon stock in the forest ecosystem compared to the baseline management (Paper I and III). Maintenance of higher stocking and use of N fertilization also gave lower CO_2 emissions per unit of energy compared to the baseline management (Paper I). Overall, at stand level the carbon neutrality was, on average, the highest with the baseline management or with the maintenance of 20% higher stocking and using 60- to 80-year rotation lengths with N fertilization, regardless of climatic conditions.

At the national level (Paper IV), when considering solely timber production, the radiative forcing (RF) had positive values (warming impact) when maintaining 20% lower stocking compared to the baseline management over a 90-year simulation period (up to 0.34 mW m^{-2}). By contrast, the maintenance of 20% higher stocking in thinning gave negative values (cooling impact), down to −0.26 mW m^{-2} (Paper IV). At the regional level (Paper III), the substitution of coal by energy biomass resulted in negative values for RF over an 80-year simulation period, regardless of management regime and climate applied. The most negative RF (up to −3.6 nW m^{-2}) was obtained if maintaining stocking 20% higher over an 80-year simulation period compared to the baseline management, and by either applying or not N fertilization and harvesting logging residues and stumps and coarse roots in final felling.

However, at the national level (Paper IV), the maintenance of 20% lower stocking in energy biomass production and utilization gave mainly positive RF values of up to 0.34 mW m^{-2}. Increasing the intensity of the energy biomass harvest in the final felling led to a higher substitution impacts. At the regional level (Paper III), the highest NPVs were obtained by using the baseline management with N fertilization, harvesting logging residues, and stumps and coarse roots, regardless of climate applied. Under the SRES B1 and A2 scenarios, the NPV and production of energy biomass slightly increased in comparison to that under the current climate, although it did not lead to an improved cooling climate impact (Paper III).

At the national level (Paper IV), the combined substitution of fossil-intensive materials (concrete and plastic) and fuels (coal and oil) by forest-based materials and energy resulted in negative values of RF (mW m^{-2}). In other words, it led to the cooling net climate impact over a 90-year simulation period. The maintenance of 20% higher stocking compared to the baseline management over a rotation and harvesting of energy biomass (from energy wood thinning and final felling, including harvest residues, stumps and coarse roots) led to the most negative values of RF. Whereas, the maintenance of 20% lower stocking and harvesting only logging residues from the final felling resulted in the smallest decrease in RF. These results show that the use of proper management and forest-based materials and energy to substitute fossil-based materials and energy would provide an effective option for mitigating climate change.

4 DISCUSSION AND CONLUSIONS

4.1 Evaluation of approaches

The main aim of this work was to study the potential of forest biomass production and utilization for mitigating climate change in boreal conditions by employing the forest ecosystem model (SIMA; Kellomäki et al. 2008) and life cycle assessment (LCA; Kilpeläinen et al. 2011). More specifically, in this work it was studied how forest management and climate change affect in boreal conditions from stand to regional level the forest biomass production (timber and energy biomass) and net climate impact of forest biomass production and utilization in substituting for fossil-intensive materials and fuels. Furthermore, the possible need to adapt the cultivation of the main Finnish tree species under the gradually changing climate was also studied.

Previous simulations with the SIMA model (Kellomäki et al. 2008; Routa et al. 2011a, 2011b) have shown good agreement with the measured values of volume growth of the main tree species on the permanent sample plots of the National Forest Inventory (NFI) throughout Finland. Furthermore, parallel simulations with the empirical growth and yield model Motti (Hynynen et al. 2002) and the SIMA model have provided good agreement for the predicted volume growth both with and without nitrogen fertilization in Norway spruce (Kellomäki et al. 2005, 2008; Routa et al. 2013). Mäkipää et al. (1998) have also earlier shown good agreement between the simulated and measured growth responses of Norway spruce to nitrogen fertilization.

The LCA tool used in this work made it possible to identify how the sink/source dynamics of the forest ecosystem as affected by management and related technosystem contribute to the mitigation potential of forest biomass production and utilization (Kilpeläinen et al. 2011). This tool has been previously used also by Alam et al. (2012, 2013), Kilpeläinen et al. (2012, 2013) and Routa et al. (2011a). The attributional LCA approach was used in the stand level analysis (Paper I) of the carbon neutrality of energy biomass utilization of Norway spruce over one rotation. This approach is close to the carbon footprint calculation, as it assesses the carbon flows of the whole production and utilization chain of a certain temporal window and management regime (Curran et al. 2005; Kilpeläinen et al. 2013). The consequential LCA approach was used in regional (Paper III) and national (Paper IV) level analyses to consider the direct and indirect impacts in comparison between the biosystem and fossil system. Thus, it showed the climate change mitigation potential provided by the substitution of fossil-intensive materials and fossil fuels by forest-based materials and energy.

4.2 Potential of forest biomass production and utilization in climate change mitigation

At the stand (Paper I) and regional (Paper III) level, it was observed that the use of longer rotations (60 to 80 years) and baseline management with and without nitrogen fertilization resulted in on average a higher mean annual timber production and NPV (with 3% interest rate). However, the mean annual timber production could be increased up to 10% by maintaining stocking 20% higher compared to the baseline management and by applying N fertilization with 60 to 80 years rotation lenghts. But this resulted in lower NPV compared to the baseline management because of delayed thinning and increased pulp wood yield on the cost of more valuable saw logs. Nitrogen fertilization one to two times over a rotation (done related to thinning) increased in relative sense more timber production than NPV (Paper I). In general, growth responses to nitrogen fertilization and effects on economic profitability are affected by the maturity stage of the stand, tree species, site fertility type and climatic conditions (Routa et al. 2011a; Bergh et al. 2014; Hedwall et al. 2014). Also in this work results were varying according to the site fertility type, thinning and N fertilization regime. The response of timber production to nitrogen fertilization was in relative terms higher on the medium fertile site than on the fertile site, which findings are in line with the previous study of Kukkola and Saramäki (1983) and Bergh et al. (2014), for example. Nitrogen fertilization done in mature forest one to three times during the rotation have usually been economically profitable, and resulted in a small and transient effect on the environment (e.g. Saarsalmi and Mälkönen, 2001; Hedwall et al. 2014; Äijälä et al. 2014).

The mean annual energy biomass production could also be increased up to 22% if stocking is maintained 20 to 30% higher compared to the baseline management and applying N fertilization, regardless of rotation length and site fertility type (Papers I, III, IV). A similar kind of result was observed with the N fertilization alone compared to the baseline management. The mean annual energy biomass production was, on average, higher for shorter (30 to 50 years) than for longer (60 to 80 years) rotations.

In this work, gradual climate warming resulted in lower mean annual timber production and NPV in Norway spruce compared to the current climate (Papers I, III). This result is due to the increased mortality of Norway spruce as a result of increase in mean annual temperature and occurrence of droughts. This was observed especially when applying longer rotation lengths (80 years). Previously, Kellomäki et al. (2008) also suggested that the growth of Norway spruce with shallow rooting will suffer the most from the effects of drought in southern Finland under the changing climate, and especially on sandy soils with relatively low soil water holding capacity. The growth of young Norway spruce, Scots pine and silver birch was also dependent on the projected climate change. The impact of climate change on growth was even contradictory between the different tree species and temperature gradients. The growth of young Norway spruce stands was clearly lower in southern and central Finland under the moderate and strong climate change (SRES A1B and A2) compared to the current climate (and SRES B1 scenario). This was observed especially when the climate change proceeded (2070-2099). The climate change effects were largest on the less fertile sites with a lower water holding capacity and with a higher occurrence of drought and mortality. However, in northern Finland, the growth of stem wood in Norway spruce was clearly higher than that under the current climate, regardless of site fertility type, climate change scenario and time span considered. The growth of stem wood in Scots pine and silver birch were under the gradually changing climate clearly higher on the fertile sites than under the current climate throughout Finland, regardless of the climate change scenario and time span considered (Paper II).

Carbon neutrality was defined in this work as the ratio of net reduction of carbon emissions when substituting fossil fuels (see e.g. Schlamadinger et al. 1995). At the stand level (Paper I), the carbon neutrality of energy biomass utilization in Norway spruce was affected by the net ecosystem CO_2 exchange and CO_2 emissions released in energy biomass combustion. The most of management regimes resulted in positive values for carbon neutrality, indicating on average lower CO_2 emissions per unit of energy produced than that caused by the use of coal instead (Paper I). The use of longer rotations (60 to 80 years), maintenance of higher stocking (20 and 30%) than the baseline management and use of nitrogen fertilization resulted in on average higher carbon neutrality, regardless of the climatic conditions.

At the regional (Paper III) and national (Paper IV) level, the climate benefits from the utilization of energy biomass were the highest if 20% higher stocking was maintained compared to the baseline management, N fertilization was applied, and the stumps and coarse roots were also harvested for energy in addition to the logging residues from the clear cut area (Papers III and IV). This was mainly due to the increase of carbon sequestration in the forest ecosystem, but it was also due to the avoidance of CO_2 emissions from the decomposition of logging residues and stumps on the site and the non-use of fossil energy. At short-term (10 to 20 years), the net CO_2 emissions of the use of energy biomass (biosystem) were slightly higher in comparison with the fossil system, and thus without the gain of climate benefits (Paper III). However, in long term, it resulted in a cooling climate impact compared to the fossil system (by replacing coal), as was also found by Sathre and Gustavsson (2011, 2012). In the long term, the net flow of CO_2 may be larger when fossil fuels are used due to emissions from both fossil fuel combustion and the decomposition of biomass fractions (Melin et al. 2010; Poudel et al. 2011).

In general, at the national level (Paper IV), forest biomass production and utilization for substituting fossil-intensive materials and fossil fuels showed positive climate benefits, as also emphasized previously by Sathre and Gustavsson (2012) and Haus et al. (2014). The highest mean reduction in radiative forcing was obtained by a management in which higher stocking was maintained through rotation compared to the baseline management, and by harvesting energy wood from energy wood thinning, and logging residues and stumps and coarse roots from final cut, over 90 years simulation period (Paper IV). In the both production systems, same amount of material (tonnes of mass) and energy (J) was produced to equalize the systems from the production point of view.

In Finland, up to 19 million tons of carbon dioxide emissions may potentially be avoided annually if higher stocking is maintained compared to the baseline management over a rotation, and by harvesting both timber, harvest residues and stumps and coarse roots (Paper IV). As a comparison, in a study of Lundmark et al. (2014), the additional mitigation potential could be more than 40 million tonnes of CO_2 eqv year^{-1} for Sweden's forests, if growth and sustainable harvest of biomass could be increased about 50 % compared to a baseline scenario. As a comparison, the emissions from road traffic were in Finland in 2012 about 11 million tonnes of CO_2 eqv and total emissions (excluding the LULUCF sector) 61 tonnes of CO_2 eqv (Statistics Finland 2014). Thus, the LULUCF sector has a crucial role in acting as a sink (26 million tonnes of CO_2 eqv in 2012), which is fluctuating mainly according the domestic commercial roundwood fellings and the annual volume increment (Statistics Finland 2014).

Forest management largely affects the yield of timber and energy biomass, but also the timing when wood products and energy biomass enter the technosystem to substitute for fossil-intensive materials and energy. For example, Eriksson et al. (2007), Sathre et al. (2010) and Routa et al. (2011b) have recommended the use of nitrogen fertilization to increase carbon sequestration of forests, and forest biomass production and utilization for materials and energy to reduce the net GHG emissions. Maintenance of higher stocking over the rotation will also increase the carbon sequestration and carbon stocks of forests compared to the baseline management, resulting in reduced radiative forcing. In turn, the maintenance of lower stocking could result in the earlier realization of substitution benefits due to earlier and increased harvesting of biomass in the first decades of the period considered (Paper IV). However, the increased decomposition of logging residues after the earlier thinnings and decrease of carbon sequestration due to a decrease in growing stock may not always compensate for the emissions over the whole time span either (Paper IV). In Finland, young and middle-aged thinning stands are currently dominant, which will affect carbon sequestration and stocks, and harvest potential in different time spans (Garcia-Gonzalo et al. 2007a; Finnish Statistical Yearbook of Forestry 2013). There are also trade-offs between short-term carbon sequestration benefits and long-term substitution benefits. Determining the optimal strategies for forest management and biomass utilization affect the net climate impacts of these actions (McKechnie et al. 2014, Sathre et al. 2013). In this work, it was estimated the maximum potential for forest biomass production considering only Finnish upland sites.

This work also showed that there are trade-offs between the NPV and carbon neutrality. In general, the higher carbon sequestration and carbon stocks of the forests provide higher carbon neutrality, but not higher NPV, and vice versa. This was also observed for the radiative forcing of energy biomass use in coal substitution (Paper III). However, some management regimes can be identified which on average provide simultaneously higher carbon neutrality, RF and NPV, such as the baseline management with and without N fertilization. As a comparison, the use of longer rotations (60 to 80 years) and maintenance of higher stocking than the baseline management with and without N fertilization resulted in higher carbon neutrality and RF, but somewhat lower NPV than the baseline management (Paper I, III, IV).

Both carbon neutrality and NPV clearly decreased if 80-year rotation length was used under the changing climate (Paper I). Thus, it would be more reasonable to have a shorter rotation length under the changing climate (especially under strong climate warming) than under the current climate (Paper I, III). For example in this work, the use of 50–70–year rotation lengths resulted in higher NPV on average, regardless of the climate applied, but somewhat lower carbon neutrality (Paper I). From the adaptive forest management point of view, to some degree, shorter rotation lengths than currently applied in Norway spruce might be needed in future, especially in southern and central Finland, to properly adapt to the foreseen climate change and decrease the risk of the mortality of trees (e.g. due to drought effects).

4.3 Conclusions

In this work, the potential of forest biomass production and utilization for mitigating climate change was studied in Finnish boreal conditions. This work showed that by modifying the business-as-usual (baseline) forest management (e.g. thinning, nitrogen fertilization and rotation length) and increasing the harvesting intensity (timber, energy biomass) it is possible to increase both forest biomass production, carbon sequestration and stocks of forests, and climate benefits of forest biomass production and utilization. The climate benefits could be increased especially by maintaining higher stocking over a rotation compared to the baseline management and using nitrogen fertilization, and by harvesting in addition to timber, also logging residues, stumps and coarse roots for energy in the final felling. However, some trade-offs exist between the economic profitability of forest biomass production and climate impacts of forest biomass production and utilization. The impacts over time are affected in addition to by forest management, biomass production and utilization also by the prevailing environmental conditions (climate, site) and forest structure (age and tree species). Gradual adaptation of forest management and utilization is needed in the future, taking into account the prevailing environmental conditions (climate, site) and uncertainties related to the climate change, to fully utilize the positive effects of climate change and reduce the negative ones. In this work, it was estimated the maximum potential of forest biomass production and utilization for mitigating climate change without considering the actual wood demand in model based analyses, which should be considered in the future research work.

REFERENCES

Aalto J., Pirinen P., Heikkinen J., Venäläinen A. (2013). Spatial interpolation of monthly climate data for Finland: comparing the performance of kriging and generalized additive models. Theoretical and Applied Climatology 112: 99–111. http://dx.doi: 10.1007/s00704-012-0716-9.

Äijälä O., Kuusinen M., Koistinen A. (edit) (2010). Recommendations for Management and Harvesting of Energy Wood. (in Finnish: Hyvän metsänhoidon suositukset energiapuun korjuuseen ja kasvatukseen), Forestry Development Centre Tapio publications. Helsinki, Finland. (In Finnish).

Äijälä O., Koistinen A., Sved J., Vanhatalo K., Väisänen P. (edit) (2014). Recommendations for Good Forest Management. (in Finnish: Hyvän metsänhoidon suositukset – metsänhoito). Publications of Forestry Development Centre Tapio, Metsäkustannus Oy. Helsinki, Finland. (In Finnish).

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

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

Alam A., Kilpeläinen A., Kellomäki S. (2012). Impacts of initial stand density and thinning regimes on energy wood production and management-related CO_2 emissions in boreal ecosystems. European Journal of Forest Research 131: 655–667. http://dx.doi: 10.1007/s10342-011-0539-8

Alam A., Kellomäki S., Kilpeläinen A., Strandman H. (2013). Effects of stump extraction on the carbon sequestration in Norway spruce forest ecosystems under varying thinning regimes with implications for fossil fuel substitution. Global Change Biology Bioenergy 5: 445–458. http://dx.doi: 10.1111/gcbb.12010

Bergh J., Freeman M., Sigurdsson B., Kellomäki S., Laitinen K., Niinistö S., Peltola H., Linder S. (2003). Modelling short-term effects of climate change on the productivity of selected tree species in Nordic countries. Forest Ecology and Management 183: 327-340. http://dx.doi: 10.1016/S0378-1127(03)00117-8

Bergh J., Nilsson U., Allen H.L., Johansson U., Fahlvik N. (2014). Long-term responses of Scots pine and Norway spruce stands in Sweden to repeated fertilization and thinning. Forest Ecology and Management 320: 118-128. http://dx.doi.org/10.1016/j.foreco.2014.02.016

Brander M., Tipper R., Hutchison C., Davis G. (2009). Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels. Technical paper, Ecometrica press, TP-090403-A.

Briceno-Elizondo E., Garcia-Gonzalo J., Peltola H., Matala J., Kellomäki S. (2006). Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions. Forest Ecology and Management 232(1-3): 152–167. http://dx.doi: 10.1016/j.foreco.2006.05.062

Buchholz T., Hurteau M.D., Gunn J., Saah D. (2015). A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies. Global Change Biology Bioenergy http://dx.doi: 10.1111/gcbb.12245

Canadell J.G., Raupach M.R. (2008). Managing forests for climate change mitigation Science (New York, N.Y.) 320: 1456–1457. http://dx.doi: 10.1126/science.1155458

Cherubini F., Strømman A.H. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. Biosource Technology 102: 437–451. http://dx.doi: 10.1016/j.biortech.2010.08.010

Cherubini F., Guest G., Strømman A.H. (2013). Bioenergy from forestry and changes in atmospheric CO_2: Reconciling single stand and landscape level approaches. Journal of Environmental Management 129: 292–301. http://dx.doi.org/10.1016/j.jenvman.2013.07.021

Curran M.A., Mann M., Norris G. (2005). The international workshop on electricity data for life cycle inventories. Journal of Cleaner Production 8: 853–862. doi 10.1016/j.jclepro.2002.03.001

Eriksson E., Gillespie A.R., Gustavsson L., Langvall O., Olsson M., Sathre R., Stendahl J. (2007). Integrated carbon analysis of forest management practices and wood substitution. Canadian Journal of Forest Research 37: 671–681. http://dx.doi: 10.1139/X06-257

Finnish Statistical Yearbook of Forestry 2013. Finnish Forest Research Institute. Vammalan kirjapaino Oy, Sastamala, Finland. 450 p.

Foster P., Ramaswamy P., Artaxo T. et al. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt,

M. Tignor and H.L Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Garcia-Gonzalo J., Peltola H., Gerendiain A.Z., Kellomäki S. (2007a). Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate. Forest Ecology and Management 241: 243–257. http://dx.doi: 10.1016/j.foreco.2007.01.008

Garcia-Gonzalo J., Peltola H., Briceno-Elizondo E., Kellomäki S. (2007b). Changed thinning regimes may increase carbon stock under climate change: A case study from a Finnish boreal forest. Climatic Change 81(3-4): 431–454.
http://dx.doi: 10.1007/s10584-006-9149-8

Ge Z.M., Kellomäki S., Peltola H., Zhou X., Väisänen H., Strandman H. (2013a). Impacts of climate change on primary production and carbon sequestration of boreal Norway spruce forests: Finland as a model. Climatic Change 118: 259–273.
http://dx.doi: 10.1007/s10584-012-0607-1

Ge Z.M., Kellomäki S., Peltola H., Zhou X., Väisänen H. (2013b). Adaptive management to climate change for Norway spruce forests along a regional gradient in Finland. Climatic Change 118(2): 275–289.
http://dx.doi: 10.1007/s10584-012-0656-5

Granda E., Camarero J.J., Gimeno T.E., Martínez-Fernández J., Valladares, F. (2013). Intensity and timing of warming and drought differentially affect growth patterns of co-occurring Mediterranean tree species. European Journal of Forest Research 132: 469–480. http://dx.doi: 10.1007/s10342-013-0687-0

Gustavsson L., Haus S., Ortiz C.A., Sathre R., Truong N.L. (2015). Climate effects of bioenergy from forest residues in comparison to fossil energy. Applied Energy 138: 36–50.
http://dx.doi.org/10.1016/j.apenergy.2014.10.013

Haus S., Gustavsson L., Sathre R. (2014). Climate mitigation comparison of woody biomass systems with inclusion of land-use in the reference fossil system. Biomass and Bioenergy 65: 136–144.
http://dx.doi.org/10.1016/j.biombioe.2014.04.012.

Hedwall P-O., Gong P., Ingerslev M., Bergh J. (2014). Fertilization in northern forests – biological, economic and environmental constrains and possibilities. Scandinavian Journal of Forest Research 29(4): 301-311.
http://dx.doi: 10.1080/02827581.2014.926096

Helin T., Sokka L., Soimakallio S., Pingoud K., Pajula T. (2013). Approaches for inclusion of forest carbon cycle in life cycle assessment – a reviw. Global Change Biology Bioenergy 5: 475–486.
http://dx.doi: 10.1111/gcbb.12016

Hynynen J., Ojansuu R., Hökkä H., Siipilehto J., Salminen H., Haapala P. (2002). Models for predicting stand development in MELA System. Finnish Forest Research Institute, Research Papers 835,116 pp.

Hyvönen R., Ågren G.I., Linder S. et al. (2007). The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in

temperate and boreal forest ecosystems: a literature review. New Phytologist 173: 463–480.
http://dx.doi: 10.1111/j.1469-8137.2007.01967.x

Hyvönen R., Persson T., Andersson S., Olsson B., Ågren G.I., Linder S. (2008). Impact of long-term nitrogen addition on carbon stocks in trees and soil in northern Europe. Biogeochemistry 89: 121–137.
http://dx.doi: 10.1007/s10533-007-9121-3

IPCC (2001). Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, R.T. Watson and the Core Team, Eds., Cambridge University Press, Cambridge and New York, 398 pp.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of WG I to the 5th Assessment report of the IPCC on Climate Change (eds. Stocker T.F., Qin D., Plattner G.K. et al.)

Jylhä K., Ruosteenoja K., Räisänen J. et al. (2009). The changing climate in Finland: estimates for adaptation studies. ACCLIM project report 2009 (in Finnish with extended abstract in English). Finnish Meteorological Institute, Reports, 4, 102.

Kellomäki S., Väisänen H., Hänninen H., Kolström T., Lauhanen R., Mattila U., Pajari, B. (1992). Sima: a model for forest succession based on the carbon and nitrogen cycles with application to silvicultural management of the forest ecosystem. Silva Carelica 22: 1–85.

Kellomäki S., Strandman H., Nuutinen T., Peltola H., Korhonen K.T., Väisänen H. (2005). Adaptation of forest ecosystems, forest and forestry to climate change. FINADAPT. Working Paper 4. Finnish Environment Institute Mimeographs 334, Helsinki.

Kellomäki S., Peltola H., Nuutinen T., Korhonen K.T., Strandman H. (2008). Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 363: 2341–2351.
http://dx.doi: 10.1098/rstb.2007.2204

Kilpeläinen A., Alam A., Strandman H., Kellomäki S. (2011). Life cycle assessment tool for estimating net CO_2 exchange of forest production. Global Change Biology Bioenergy 3: 461–471.
http://dx.doi: 10.1111/j.1757-1707.2011.01101.x

Kilpeläinen A., Kellomäki S., Strandman H. (2012). Net atmospheric impacts of forest bioenergy production and utilization in Finnish boreal conditions. Global Change Biology Bioenergy 4: 811-817.
http://dx.doi: 10.1111/j.1757-1707.2012.01161.x

Kilpeläinen A. (2013). Life cycle carbon assessment of bioenergy production. In publication: Forest Bioenergy Production: Management carbon sequestration and adaptation. Ed. Kilpeläinen A, Kellomäki S, Alam A. Springer., ISBN: 978-1-4614-8390-8.

Kirkinen J., Palosuo T., Holmgren K., Savolainen I. (2008). Greenhouse impact due to the use of combustible fuels: Life cycle viewpoint and relative radiative forcing commitment. Environmental Management 42: 458–469.
http://dx.doi: 10.1007/s00267-008-9145-z

Klein D., Wolf C., Schulz C., Weber-Blaschke G. (2015). 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and methodical proposal for the LCA of forest production. International Journal of Life Cycle Assessment. http://dx.doi: 10.1007/s11367-015-0847-1

Kolström M., Lindner M., Vilén T. et al. (2011). Reviewing the science and implementation of climate change adaptation measures in European forestry. Forests 2: 961–982.

Kukkola M., Saramäki J. (1983). Growth response in repeatedly fertilized pine and spruce stands on mineral soils. Communicationes Instituti Forestalis Fenniae 114:1–55.

Lamers P., Junginger M. (2013). The 'debt' is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. Biofuels Bioproducts & Biorefining 7: 373–385. http://dx.doi: 10.1002/bbb.1407

Liski J., Pussinen A., Pingoud K., Mäkipää R., Karjalainen T. (2001). Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research 31: 2004–2013. http://dx.doi: 10.1139/cjfr-31-11-2004

Lundmark T., Bergh J., Hofer P. et al. (2014). Potential roles of Swedish forestry in the sontext of climate change mitigation. Forests 5(4): 557–578. http://dx.doi: 10.3390/f5040557

Malmsheimer R.W., Bowyer J.L., Fried J.S. et al. (2011). Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy. Journal of Forestry 109(7S):S7–S50.

Matala J., Ojansuu R., Peltola H., Raitio H., Kellomäki S. (2006). Modelling the response of tree growth to temperature and CO_2 elevation as related to the fertility and current temperature sum of a site. Ecological Modelling 199: 39–52. http://dx.doi: 10.1016/j.ecolmodel.2006.06.009

Matala J., Kärkkäinen L., Härkönen K., Kellomäki S., Nuutinen T. (2009). Carbon sequestration in the growing stock of trees in Finland under different cutting and climate scenarios. European Journal of Forest Research 128: 493-504. http://dx.doi: 10.1007/s10342-009-0299-x

Meehl G.A., Covey C., Delworth T., et al. (2007). The WCRP CMIP3 Multimodel Dataset: A new era in climate change research. Bulletin of American Meteorological Society 88: 1383–1394. http://dx.doi: 10.1175/BAMS-88-9-1383.

Melillo J.M., Reilly J.M., Kicklighter D.W. et al. (2009). Indirect emissions from biofuels: how important? Science (New York, N.Y.) 326: 1397–1399. http://dx.doi: 10.1126/science.1180251

Melin Y., Petersson H., Egnell G. (2010). Assessing carbon balance trade-offs between bioenergy and carbon sequestration of stumps at varying time scales and harvest intensities. Forest Ecology and Management 260: 536–542. http://dx.doi: 10.1016/j.foreco.2010.05.009

Mitchell S.R., Harmon M.E., O'Connell K.E.B. (2012). Carbon debt and carbon sequestration parity in forest bioenergy production. Global Change Biology Bioenergy 4(6): 818-827. http://dx.doi: 10.1111/j.1757-1707.2012.01173.x.

Mäkipää R., Karjalainen T., Pussinen A., Kukkola M., Kellomäki S., Mälkönen E. (1998). Applicability of a forest simulation model for estimating effects of nitrogen deposition on a forest ecosystem: Test of the validity of a gap-type model. Forest Ecology and Management 108: 239–250.

Nakićenović N., Alcamo J., Davis G., et al. (2000). Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U.K., 599 pp. Available online at: http://www.grida.no/climate/ipcc/emission/index.htm

National energy and climate strategy. (2013). Energy and the climate 8/2013. Ministry of Employment and the Economy. MEE Publications. Edita Publishing Oy / Ab / Ltd. 55 p. ISSN (online) 1797-3562. ISBN (pdf) 978-952-227-750-3.

Nunery J.S., Keeton W.S. (2010). Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products. Forest Ecology and Management 259: 1363–1375.
http://dx.doi: 10.1016/j.foreco.2009.12.029

Poudel B.C., Sathre R., Gustavsson L., Bergh J., Lundström A., Hyvönen R. (2011). Effects of climate change on biomass production and substitution in north-central Sweden. Biomass & Bioenergy 35: 4340–4355.
http://dx.doi: 10.1016/j.biombioe.2011.08.005

Poudel B.C., Sathre R., Bergh J., Gustavsson L., Lundström A., Hyvönen, R. (2012). Potential effects of intensive forestry on biomass production and total carbon balance in north-central Sweden. Environmental Science & Policy 15: 106–124.
http://dx.doi: 10.1016/j.envsci.2011.09.005

Ramaswamy W., Boucher O., Haigh J. et al. (2001). Radiative forcing of climate change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (eds Houghton JT et al.), pp. 349–416. Cambridge University Press, Cambridge, UK and New York, NY.

Repo A., Tuomi M., Liski J. (2011). Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. Global Change Biology Bioenergy 3: 107–115.
http://dx.doi: 10.1111/j.1757-1707.2010.01065.x

Repo A., Känkänen R., Tuovinen J-P., Antikainen R., Tuomi M., Vanhala P., Liski J. (2012). Forest bioenergy climate impact can be improved by allocating forest residue removal. Global Change Biology Bioenergy 4: 202–212.
http://dx.doi: 10.1111/j.1757-1707.2011.01124.x

Repo A., Tuovinen J-P., Liski J. (2015). Can we produce carbon and climate neutral forest bioenergy? Global Change Biology Bioenergy 7:253–262.
http://dx.doi: 10.1111/gcbb.12134

Routa J., Kellomäki S., Kilpeläinen A., Peltola H., Strandman H. (2011a). Effects of forest management on the carbon dioxide emissions of wood energy in integrated production of timber and energy biomass. Global Change Biology Bioenergy 3: 483–497.
http://dx.doi: 10.1111/j.1757-1707.2011.01106.x

Routa J., Kellomäki S., Peltola H., Asikainen A. (2011b). 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.

http://dx.doi: 10.1093/forestry/cpr003

Routa J., Kellomäki S., Peltola H. (2012). 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 5: 106–123.
http://dx.doi: 10.1007/s12155-011-9115-9

Routa J., Kellomäki S., Strandman H., Bergh J., Pulkkinen P., Peltola H. (2013). The timber and energy biomass potential on intensively managed cloned Norway spruce stands. Global Change Biology Bioenergy 5:43–52.
http://dx.doi: 10.1111/gcbb.12002

Saarsalmi A., Mälkönen E. (2001). Forest fertilization research in Finland: a literature review. Scandinavian Journal of Forest Research 16: 514-535.
http://dx.doi: 10.1080/02827580152699358

Sathre R., Gustavsson L., Bergh J. (2010). Primary energy and greenhouse gas implications of increasing biomass production through forest fertilization. Biomass & Bioenergy 34: 572–581.
http://dx.doi: 10.1016/j.biombioe.2010.01.038

Sathre R., Gustavsson, L. (2011). Time-dependent climate benefits of using forest residues to substitute fossil fuels. Biomass & Bioenergy 35: 2506–2516.
http://dx.doi: 10.1016/j.biombioe.2011.02.027

Sathre R., Gustavsson, L. (2012). Time-dependent radiative forcing effects of forest fertilization and biomass substitution. Biogeochemistry, 109: 203–218.
http://dx.doi: 10.1007/s10533-011-9620-0

Sathre R., Gustavsson L., Haus S. (2013). Time dynamics and radiative forcing of forest bioenergy systems. In. Kellomäki et al. (2013) Forest bioenergy production: Management, carbon sequestration and adaptation. Springer, New York, US. 268 p.
http://dx.doi: 10.1007/978-1-4614-8391-5

Schlamadinger B., Spitzer J., Kohlmaier G.H., Lüdeke M. (1995). Carbon balance of bioenergy from logging residues. Biomass & Bioenergy 8: 221–234.

Searchinger T., Heimlich R., Houghton R.A. et al. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science (New York, N.Y.) 319: 1238–1240.
http://dx.doi: 10.1126/science.1151861

Statistics Finland (2014). Suomen kasvihuonekaasupäästöt 1990-2012. Katsauksia 2014/1. Ympäristö ja luonnonvarat. Helsinki, Finland. 57 p. and appendices.

Tamm, C. (1991). Nitrogen in terrestrial ecosystems, questions of productivity, vegetational changes and ecosystem stability. Ecological Studies 81:115.

Taylor K.E., Stouffer R.J., Meehl G.A. (2012). An Overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93: 485–498.
http://dx.doi: 10.1175/BAMS-D-11-00094.1.

Ter-Mikaelian M.T., McKechnie J., Colombo S., Chen J., MacLean H. (2011). The carbon neutrality assumption for forest bioenergy: A case study for northwestern Ontario. Forest Chronicle 87: 644–652.

Ter-Mikaelian M.T., Colombo S.J., Chen J. (2015). The burning question: Does forest bioenergy reduce carbon emissions? A Review of common misconceptions about forest carbon accounting. Journal of Forestry 113(1): 57-68. http://dx.doi.org/10.5849/jof.14-016

Torvelainen J., Ylitalo E., Nouro, P. (2014). Puun energiakäyttö 2013. Metsätilastotiedote 31/2014.7 p. (In Finnish).

Venäläinen A., Tuomenvirta H., Pirinen P., Drebs A. (2005). A Basic Finnish climate data set 1961-2000- description and illustrations. Reports of the Finnish Meteorological Institute, 5, 27 p.