GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012) **4**, 202–212, doi: 10.1111/j.1757-1707.2011.01124.x

Forest bioenergy climate impact can be improved by allocating forest residue removal

ANNA REPO*†, RIINA KÄNKÄNEN*, JUHA-PEKKA TUOVINEN‡, RIINA ANTIKAINEN*, MIKKO TUOMI*§, PEKKA VANHALA* and JARI LISKI*

*Finnish Environment Institute, PO Box 140, FIN-00251, Helsinki, Finland, †Department of Mathematics and Systems Analysis, Aalto University, PO Box 11100, FIN-00076, Aalto, Finland, ‡Finnish Meteorological Institute, PO Box 503, FIN-00101, Helsinki, Finland, §Department of Mathematics and Statistics, University of Helsinki, PO Box 68, FIN-00014, Helsinki, Finland

Abstract

Bioenergy from forest residues can be used to avoid fossil carbon emissions, but removing biomass from forests reduces carbon stock sizes and carbon input to litter and soil. The magnitude and longevity of these carbon stock changes determine how effective measures to utilize bioenergy from forest residues are to reduce greenhouse gas (GHG) emissions from the energy sector and to mitigate climate change. In this study, we estimate the variability of GHG emissions and consequent climate impacts resulting from producing bioenergy from stumps, branches and residual biomass of forest thinning operations in Finland, and the contribution of the variability in key factors, i.e. forest residue diameter, tree species, geographical location of the forest biomass removal site and harvesting method, to the emissions and their climate impact. The GHG emissions and the consequent climate impacts estimated as changes in radiative forcing were comparable to fossil fuels when bioenergy production from forest residues was initiated. The emissions and climate impacts decreased over time because forest residues were predicted to decompose releasing CO_2 even if left in the forest. Both were mainly affected by forest residue diameter and climatic conditions of the forest residue collection site. Tree species and the harvest method of thinning wood (whole tree or stem-only) had a smaller effect on the magnitude of emissions. The largest reduction in the energy production climate impacts after 20 years, up to 62%, was achieved when coal was replaced by the branches collected from Southern Finland, whereas the smallest reduction 7% was gained by using stumps from Northern Finland instead of natural gas. After 100 years the corresponding values were 77% and 21%. The choice of forest residue biomass collected affects significantly the emissions and climate impacts of forest bioenergy.

Keywords: bioenergy, climate change mitigation, logging residues, radiative forcing, soil carbon, Yasso07

Received 15 April 2011 and accepted 20 July 2011

Introduction

Biomass-based fuels may be used to replace fossil fuels in order to reduce greenhouse gas (GHG) emissions of energy production and mitigate climate change. It has been common to think that bioenergy is a carbon neutral energy source because carbon emitted into the atmosphere through combustion will be absorbed again by the next generation of growing vegetation (Schlamadinger *et al.*, 1995; Wihersaari, 2005b; Stupak *et al.*, 2007).

Following this philosophy, the member states of the European Union are increasing bioenergy production as part of their climate and energy policies (EU energy and climate package 2008; Beurskens & Hekkenberg, 2011). For example, Finland aims to increase the use of logging residues for energy production from 3.6 $Mm^3\ yr^{-1}$ in 2006 to 13.5 $Mm^3\ yr^{-1}$ by 2020 (Ministry of Employment and the Economy of Finland 2008, 2010).

Recently however, the carbon neutrality of biofuels has been questioned because of land-use-change-related emissions (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009; Melillo *et al.*, 2009). For example, deforestation and a consequent conversion of the forest to an energy crop plantation may reduce the carbon stocks of biomass or soil or both, and thus cause GHG emissions into the atmosphere. These emissions are not limited to land use changes but bioenergy production may also reduce the carbon stocks within the same land use. This may happen, for example, when residues of forest harvests are removed from forests for bioenergy production in addition to removals of industrial round wood (Schlamadinger *et al.*, 1995; Palosuo *et al.*, 2001; Repo *et al.*, 2011).

Correspondence: Anna Repo, tel. + 358 400 148 652, fax + 358 954 902 190, e-mail: anna.repo@ymparisto.fi

Increasing biomass removals from forests because of bioenergy production can both decrease the carbon stocks of the forests and reduce their carbon sink capacity. These alterations have been described using terms like 'carbon debt', 'carbon deficit' or 'indirect carbon dioxide (CO_2) emissions' resulting from changes in carbon stocks (Palosuo *et al*., 2001; Searchinger *et al*., 2008, 2009; Melin *et al*., 2010; Zanchi *et al*., 2010; Repo *et al*., 2011). These changes in the carbon budget of forests are crucial to the overall GHG emissions of bioenergy as the other emissions from the production chain of forest bioenergy, i.e. those from machines used in biomass harvesting, processing and transport, are usually small in comparison (Börjesson, 1996; Forsberg, 2000; Wihersaari, 2005b; Eriksson & Gustavsson, 2008).

The GHG emissions affect climate by changing the radiative energy balance of the Earth. In addition to the emissions themselves, the effects on this balance depend on the background concentrations, the warming potential, and the residence time of different GHGs in the atmosphere. For this reason, following the development of emissions over time only gives limited information about the potential climate impacts of the emissions (e.g. Kirkinen *et al*., 2008). The concept of radiative forcing (RF) can be used to assess and compare the anthropogenic and natural drivers of climate change, i.e. to estimate their potential climate impact (IPCC 2007). In this study, the RF was used as a measure of the climate impacts of forest resources used as a bioenergy feedstock.

When bioenergy is produced from forest harvest residues the GHG emissions depend mainly on the decomposition rate of the removed forest residues if they were left in forest to decompose (Repo *et al*., 2011). Removals of slowly decomposing residues reduce the amount of carbon stored in forests for a longer time, and thus this practice causes larger GHG emissions over time than removals of more quickly decomposing residues. Allocating bioenergy production to quickly decomposing residues provides a means to reduce the GHG emissions from forest bioenergy produced from forest residues (Repo *et al*., 2011).

Important factors affecting the decomposition rate of forest residues are the size of the residues, climate conditions, and the chemical quality of the residues, which is associated with tree species (e.g. Harmon *et al*., 1986, 2000). It is unknown how much the emissions and the consequent climate impacts vary among different forest bioenergy options or how much the choice of forest residues used for energy production may affect the climate benefits achieved using forest bioenergy within a country. Country-scale analyses are relevant from the point of view of climate policy because in the EU, the emission reduction targets are country-specific.

The objective of this study was to assess the variability of GHG emissions and climate impacts caused by using different forest harvest residues for bioenergy production in Finland. Our analyses covered changes in the carbon budget of forests, and the GHG emissions from bioenergy production chains.

Materials and methods

Estimating CO_2 emissions resulting from changes in carbon stocks

We studied theoretical cases in which (i) young stand thinning wood, (ii) branches from final felling sites, or (iii) stumps from final felling sites were collected for energy production, in addition to the industrial wood (saw logs, pulpwood) harvesting. In the reference cases, the forest residues and thinning wood were left to decompose in the forest. We assumed that the removal of the residues does not affect to the growth of the next plant generation. Hence in all cases, the growing trees absorb and store carbon to biomass equally. The only difference between the forest residue removal cases and reference cases is that the carbon stored in the residues is emitted into the atmosphere instantly through combustion, while in the reference cases the emissions take place gradually through decomposition.

To estimate the CO_2 emissions resulting from the reductions in forest carbon stock, we simulated the decomposition of the forest residues collected for energy using the dynamic soil carbon model Yasso07 (Tuomi *et al*., 2009, 2011; www.environment.fi/syke/yasso). The basic concept of the model is that the decomposition rate of different types of soil carbon inputs depends on the chemical composition of the input types and climate conditions. The decomposition rate of woody litter depends also on the diameter of litter. The measurements used to develop the model include an extensive data set on decomposition of nonwoody litter across Europe, and North and Central America (n = 9605), data sets on the decomposition of woody litter in Finland and neighboring regions in Estonia and Russia (n = 2102) (Mäkinen *et al*., 2006a; Palviainen *et al*., 2008; Vávrová *et al*., 2009; Tarasov & Birdsey, 2001), and measurements on the accumulation of soil organic carbon in Finland (n = 86) (Liski & Westman, 1995, 1997; Liski *et al*., 1998). The Yasso07 is suitable for this study because the data used to develop the model cover the simulated scenarios well. In addition, the model has been shown to give unbiased estimates of the decomposition of various plant species across a wide range of ecosystems and climatic conditions (Tuomi *et al*., 2009), and woody litter decomposition of spruce (*Picea* sp.), pine (*Pinus* sp), and birch (*Betula* sp.) in boreal conditions (Tuomi *et al*., 2011).

The variability in the emissions resulting from the changes in carbon stocks was studied by simulating the decomposition of forest residues that varied in biomass diameter, climatic conditions of the biomass removal site, tree species and young stand thinning method. We simulated the decomposition of branches (2 cm in diameter), young stand thinning wood

(10 cm in diameter) and stumps (30 cm in diameter) in the Pirkanmaa region in Southern Finland (61.88°N, 23.72°E). To study the effect of climate on the decomposition, we repeated these simulations for the climatic conditions of Savukoski region in Northern Finland (67.92°N, 28.16°E). The studied tree species were Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and Silver birch (*Betula pendula*), although more calculations were done for the Norway spruce because the annual technical harvesting potential of spruce crowns and stumps from final felling sites and from young stand thinnings is over twice that of the corresponding pine biomass in Finland (Laitila *et al*., 2008). The effect of young stand thinning method, i.e. whether removed as whole tree or stem-only harvesting was also studied. Needles were assumed to be left at the harvest site, except when young stand thinning wood was collected as whole trees. The studied variables correspond to the current energy wood management practices in Finland (Kuusinen & Ilvesniemi, 2008; Äijälä *et al*., 2010), except for the fact that collecting whole spruce trees from young stands is not recommended because of the risk of nutrient deficiency (Äijälä *et al*., 2010). The other input variables used in the simulations are presented in Table 1.

The CO_2 emissions resulting from the changes in forest carbon stocks were taken to be equal to the amount of carbon remaining in the thinning wood, branches or stumps over time, if these were left to decay at the forest harvest site (Repo *et al*., 2011). To calculate emissions from collection and combustion of forest residues, it was assumed that each year a parcel of forest was managed to extract the residues, and an equal amount of forest residues was extracted moving from one logging site to another for a period of 100 years. The cumulative emissions were calculated summing up the amount of carbon remaining in the forest residues over parcels and time. These emissions were related to the cumulative amount of bioenergy produced from the collected biomass. Consequently, our calculations were independent of the area or the total harvest. As the moisture content of wood chips affects the energy content (Hakkila, 2004), we applied compartment-specific net caloric values at combustion (MJ kg^{-1}) calculated with the BS EN 14961-1: 2010 standard by using the net caloric values for dry biomass by Alakangas (2005). When moisture content at combustion was assumed to be for 35% (m/m) for stumps and 40% for other forest residues (Hakkila, 2004; Mäkinen *et al*., 2006b), the net calorific value of forest residues ranged from 10.4 to 11.8 MJ kg^{-1} depending on tree part and tree species. The effect of moisture content on the emissions was studied by varying the wood chip moisture content within 35–60% for stumps and within 40–60% for other biomass (Hakkila, 2004; Mäkinen *et al*., 2006b). The carbon content of the forest residues was assumed to equal to 50% of dry wood (m/m) (Alakangas, 2005).

Estimating GHG emissions from collecting, chipping, transporting and combusting of the forest residues

To estimate the climate impacts of forest residue energy use, the CO_2, CH_4 and N_2O emissions from the forest bioenergy production chain were estimated on the basis of literature (Table 2), and added to emissions resulting from carbon stock changes. The phases taken into account included forest end transportation, chipping in intermediate storage, long distance transportation and transportation of machinery. The non-CO_2 emissions from combustion were included. In case of young stand thinning wood also thinning by harvester, and in case of stumps the excavation were taken into account. Commuter traffic was not considered. The emissions from production chain were additional compared to reference cases in which harvest residues were not collected. The efficiency of machinery and their fuel consumption were calculated on the basis of the figures presented by A. Alam, A. Kilpeläinen and S. Kellomäki

Table 1 The values of the input variables used in the Yasso07 model

Chemical composition of litter	Average ± 2 SD (%)		
	Spruce	Pine	Birch
Branch/stem/stump			
Acid hydrolysable compounds	68 ± 8	68 ± 8	76 ± 10
Water soluble compounds	1 ± 2	2 ± 2	1 ± 2
Ethanol soluble compounds	1 ± 1	1 ± 1	0 ± 1
Klason lignin (neither hydrolysable nor soluble compounds)	30 ± 2	27 ± 2	24 ± 2
Foliage			
Acid hydrolysable compounds	50 ± 6	51 ± 6	39 ± 4
Water soluble compounds	9 ± 10	13 ± 14	9 ± 10
Ethanol soluble compounds	5 ± 4	10 ± 8	5 ± 4
Klason lignin (neither hydrolysable nor soluble compounds)	35 ± 2	25 ± 2	35 ± 2
Climate			
	Southern Finland	Northern Finland	
Mean annual temperature	3.2 °C	−0.8 °C	
Temperature amplitude	11.6 °C	14.2 °C	
Precipitation	681 mm	565 mm	

The chemical composition of woody litter is based on several individual studies (Hakkila, 1989) and that of foliage on measurements by Berg *et al*. (1984), Berg & Wessén (1984) and Berg *et al*. (1991). The standard deviation (SD) values are based on coefficient of variation calculated from the data of Vávrová *et al*. (2009). The proportional distribution of biomass components (branches, stem, foliage) of whole tree thinning wood is taken from Voipio & Laakso (1992).The climate values represent the averages during 1971–2000 (Drebs *et al*., 2002). The temperature amplitude means a half of the difference between the mean temperatures of the warmest and the coldest month of the year.

Table 2 The values for estimating greenhouse gas emissions from collecting, chipping, transporting forest residues (Lipasto/LIISA, 2009, A. Alam, A. Kilpeläinen and S. Kellomäki, unpublished results)

Phases	Productivity/capacity	Fuel consumption
Forest operations		
Thinning by harvester	8.2 m^3 h^{-1}	12 L h^{-1}
Stump excavation	13 m^3 h^{-1}	15 L h^{-1}
Transport and chipping		
Forwarding (forest-end)	11.8 m^3 h^{-1}	8.5 L h^{-1}
Chipping	150 m^3 h^{-1}	60 L h^{-1}
Transportation with trucks	125 m^3 per truck	0,496 L km^{-1} (full load, highway)
		0,327 L km^{-1} (empty load, highway)
		0.901 L km^{-1} (full load, urban)
		0.508 L km^{-1} (empty load, urban)

(unpublished results). The GHG emission factors for machinery were obtained from Lipasto/TYKO (2009) database. Long distance transportation was assumed to be done by EURO 5 trucks (payload 40 t corresponding to a wood chip volume of 125 m^3) (Jyländki, 2010) with full load and empty return load. The EURO 5 was considered to be the best emission category choice for this kind of a future-oriented study. The data for transportation fuel consumption and GHG emissions were obtained from the Lipasto/LIISA (2009) database. The transportation distances were assumed to be 70 km in Pirkanmaa region in Southern Finland and 95 km in Savukoski region in Northern Finland. In both cases, the transport distance in urban area was assumed to account for 7.5 km. The transportation of machinery was calculated by assuming that their share of GHG emissions in each forest energy chain equals the share of total emissions as calculated by Mäkinen *et al.* (2006b).

Calculation of climate impacts

The RF, expressed in W m^{-2}, was used for quantitative comparisons of the potential climate impact resulting from the emissions due to different energy production options. The RF is defined as the change in the net irradiance at the tropopause following, for example, an increase in a GHG concentration (Shine *et al.*, 2003; IPCC 2007). A positive RF tends to warm the surface of the Earth, whereas a negative RF cools the surface. To estimate the climate impacts of forest residue bioenergy production, we calculated the increase of the atmospheric GHG concentrations caused by the emissions from this activity and the consequent development of RF. The emissions include emissions resulting from reduction in soil carbon stock and production chain. The RF due to these emissions was compared to the RF due to the production chain and combustion emissions of different fossil fuels.

We calculated the changes in the RF resulting from GHG emissions from forest residue energy production with the modified version (Lohila *et al.*, 2010) of the REFUGE model (Monni *et al.*, 2003). In this model, the RF change is estimated by integrating the response function related to an instantaneous concentration pulse annually over time, taking into account the annual variation in the emissions and background concentrations of the long-lived GHGs considered (CO_2, CH_4 and N_2O). Our study period was 2010–2110, and we calculated the RF change for each GHG as a marginal change with respect to a varying reference concentration, which was assumed to follow the SRES A2 scenario (IPCC 2001). After the end of this scenario in 2100, the concentrations were linearly extrapolated for the remaining 10 years. The climate impact of the forest residue energy was expressed as the sum of the RF changes obtained for each GHG. We calculated the instantaneous RFs to follow yearly changes in the RF, and cumulative RFs to account for the warming impact of long-lived GHG of the emissions from the previous years. In both cases, 1 PJ of primary energy was produced each year. The GHG emission factors used in the calculations are shown in Table 3.

Table 3 The greenhouse gas (GHG) emission factors for forest residue bioenergy and fossil fuel production chain and combustion. Values for fossil fuels are estimates of the entire fuel cycle emissions (Ecoinvent centre 2007, Statistics Finland 2011). Values for forest residue bioenergy include emissions from the production chain and combustion and depend on tree species and part (Hakkila, 2004; Alakangas, 2005; Mäkinen *et al.*, 2006b; Tsupari *et al.*, 2006). Global warming potentials (GWP) relative to CO_2 for 100 years (IPCC 2001) were used to calculate total GHG emissions in CO_2 equivalents

Energy source	CO_2 (g MJ^{-1})	CH_4 (g MJ^{-1})	N_2O (g MJ^{-1})	Total GHG emissions (g CO_2 eq. MJ^{-1}) (GWP 100)
Forest residues	103–105	3–6 × 10^{-5}	3 × 10^{-3}	104–108
Coal	96	6 × 10^{-1}	6 × 10^{-5}	110
Heavy fuel oil	88	4 × 10^{-2}	2 × 10^{-4}	89
Natural gas	68	4 × 10^{-1}	2 × 10^{-4}	78

Results

GHG emissions

Among the factors studied biomass size and climate conditions were the most important ones affecting the longevity of carbon in the harvest residues left in the forest (Fig. 1). For example, there were still 64% of the large-sized spruce stumps remaining in Southern Finland after 20 years of decomposition while this figure was 45% for the smaller-sized thinning wood and 24% for branches. In Northern Finland, these figures were somewhat larger, 73%, 55%, and 28%, respectively. On the other hand, there were only small differences in the decomposition rate between different tree species, with birch residues decomposing slightly faster than the residues of coniferous tree species studied (data not shown).

The decomposition rate of the forest residues (see Fig. 1) had a crucial effect on the GHG emissions of bioenergy production from the residues over time. This was because, firstly, this rate determined how much the carbon stock of forest was reduced as a result of removing the harvest residues, and, secondly, the emissions from the bioenergy production chain, e.g. from machines used, were relatively small (Fig. 2).

When the practice of bioenergy production was started, the emissions per energy unit were equal to the emissions from combustion plus the small emissions from the production chain (Fig. 2). The emissions dropped fairly quickly, if forest residues with a high decomposition rate were used for energy production, or more slowly, if residues more resistant to decomposition were used. For example in spruce forests in Southern Finland after 20 years, the emissions of branch bioenergy dropped from 105 to 47 g CO_2 eq. MJ^{-1}, whereas the emissions of stump bioenergy were reduced from 105 to 92 g CO_2 eq. MJ^{-1}. After 100 years, the emissions of branch bioenergy were reduced to 21 g CO_2 eq. MJ^{-1}, and those of stump bioenergy to 56 g CO_2 eq. MJ^{-1}. In Northern Finland, these emission figures were somewhat higher as a result of lower decomposition rates.

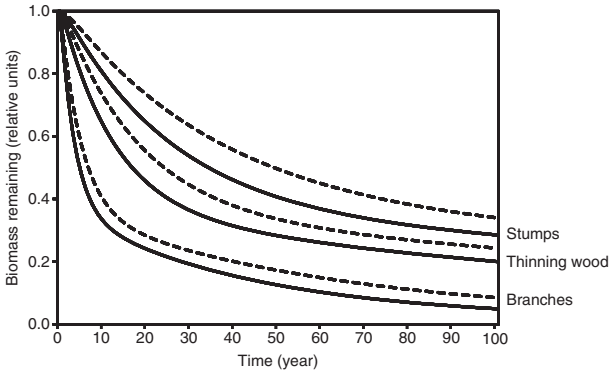

Fig. 1 Mass remaining of decomposing Norway spruce stumps (diameter 30 cm), young stand delimped thinning wood (diameter 10 cm) and branches (diameter 2 cm) over a 100 year period after start of the decomposition in Northern Finland (dotted line) and Southern Finland (solid line) as simulated the using Yasso07 model. Model input values are in shown in Table 1.

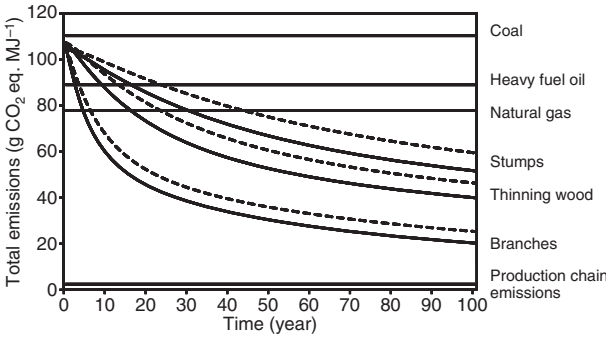

Fig. 2 Total greenhouse gas emission per energy content from producing energy from Norway spruce stumps (diameter 30 cm), young stand delimped thinning wood (diameter 10 cm) and branches (diameter 2 cm) over a 100 year period after start of the practice in Northern Finland (dotted line) and Southern Finland (solid line) and the entire fuel cycle emissions of some fossil fuels. The total emission estimates of forest bioenergy include emissions resulting from the changes in carbon stocks (Fig. 1) and the emissions from the production chain including collecting, transporting, chipping and combusting the forest residues (Fig. 4).

Compared to fossil fuels at first, the GHG emissions from using bioenergy were nearly as high as the emissions from using coal, 16–21% higher compared to the use of heavy fuel oil and 32–39% higher compared to natural gas (Fig. 2). After 20 years in spruce forests in Southern Finland, the emissions from using branch bioenergy were 40–57% smaller compared to the different fossil fuels. The emissions from using stump bioenergy were still 18% higher compared to natural gas but already 16% lower compared to coal. After 100 years, the emissions from using branch bioenergy were 73–81% lower compared to the different fossil fuels and the emissions from stump bioenergy 29–49% lower.

The GHG emissions from the forest bioenergy production chain originated from several parts of the chain, namely transport at the harvest site, chipping, machine transfer, thinning, stump harvesting, long-distance transport, and other GHG emissions than CO_2 from combustion. The sum of these emissions ranged from 1.8 to 2.2 g CO_2 eq. MJ^{-1} depending on harvest residue

but it was always small compared to the emissions from the decreased carbon stock of harvest residues in forest (Fig. 4). The production chain emissions were 2–3% of the total emissions at the start of the forest energy production, and correspondingly 4–10% after the energy production was continued for 100 years (Fig. 3).

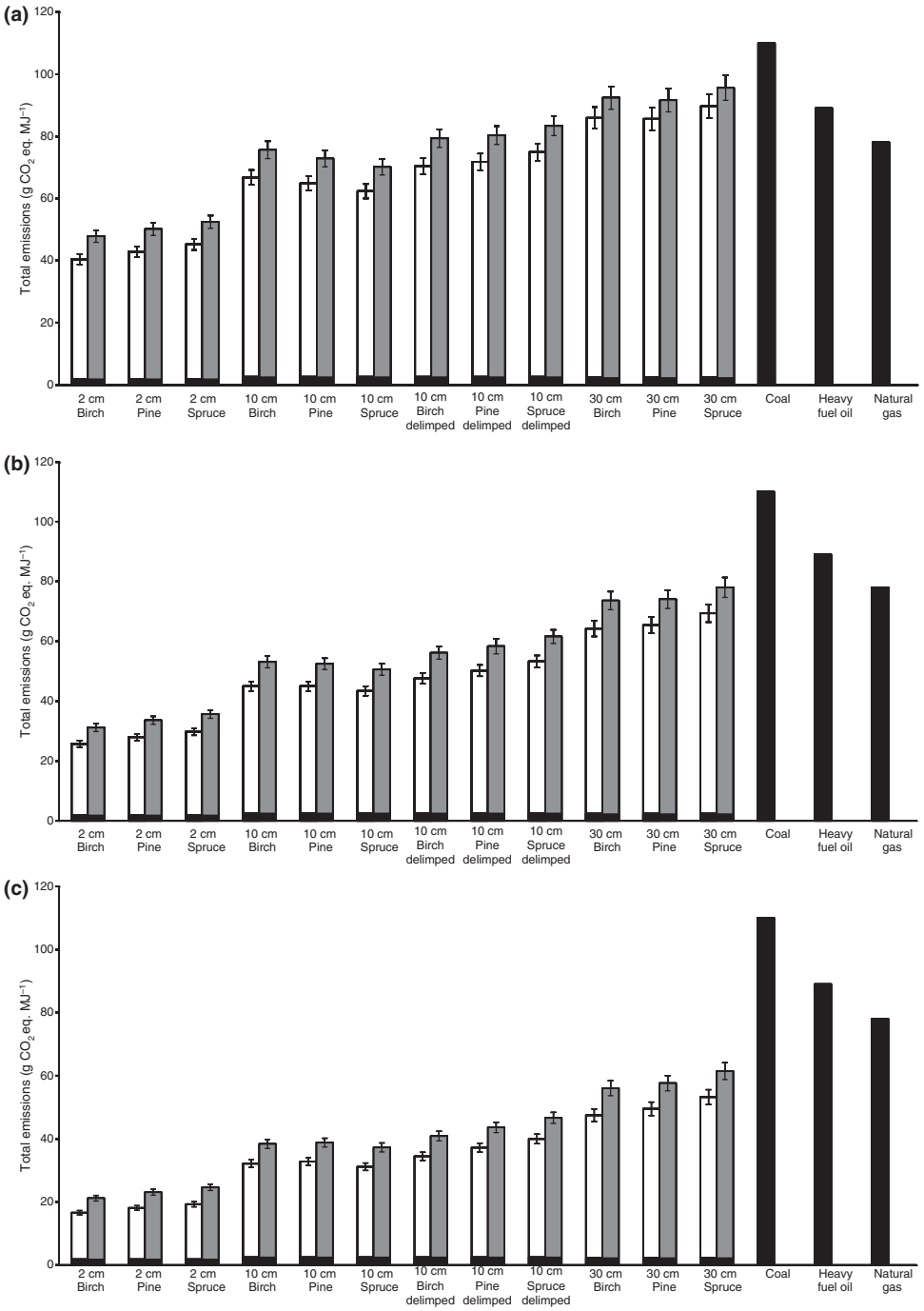

Fig. 3 The total greenhouse gas emissions from using branches (2 cm), thinning wood (10 cm) and stumps (30 cm) of prevailing tree species for energy production for (a) 20 years (b) 50 years and (c) 100 years, if forest residues are collected from Southern Finland (white) and Northern Finland (gray), and the corresponding full fuel cycle emissions from fossil fuels. The share of emissions from the forest fuel production chain (Fig. 4) is indicated with black columns. The error bars represent the uncertainty resulting from the parameter values of the Yasso07 model, chemical composition of forest residues and variability in the energy content of forest residue depending on the moisture content.

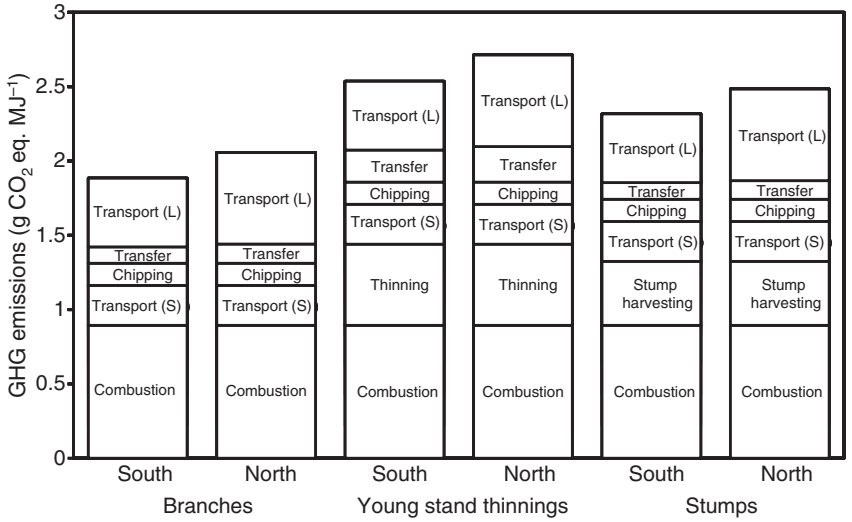

Fig. 4 The greenhouse gas (GHG) emissions from the forest bioenergy production chain when the branches and stumps from final felling sites, and the young-stand thinning wood are collected. The production chain emissions include non-CO_2 emissions from combustion; CO_2, CH_4 and N_2O emissions from transport at the harvest site (Transport S), chipping, machine transfer, thinning, stump harvesting, and long-distance transport (Transport L).

Following the differences in the decomposition rate (see Fig. 1), the size of the harvest residues had the largest effect on the GHG emissions of bioenergy production (Fig. 3). The second most important factor affecting the emissions was the difference in climate conditions between Southern and Northern Finland. On the other hand, the method of collecting the thinning wood (stem-only or whole wood) or tree species had only small effects on the emissions (Fig. 3). The lowest GHG emissions occurred when birch branches in Southern Finland were used for bioenergy production and the highest when spruce stumps in Northern Finland were used (Fig. 3). For example, after 20 years, the emissions of this birch branch bioenergy were 42 g CO_2 eq. MJ^{-1}, and those of spruce stump bioenergy 2.4 times as high, 98 g CO_2 eq. MJ^{-1}. The relative difference between these bioenergy options increased over time. After 100 years, the corresponding emissions from the spruce stump bioenergy 63 g CO_2 eq. MJ^{-1} were 3.5 times as high as the emissions from the birch branch bioenergy.

Changes in RF

The emissions from bioenergy production increased the atmospheric concentration of GHGs, and caused a change in RF. The instantaneous RF change resulting from continued bioenergy production leveled off over time sooner than that due to energy use of fossil fuels (Fig. 5a). This results from the difference in emissions between the bioenergy case and the reference case, in which the forest residues decompose slowly releasing

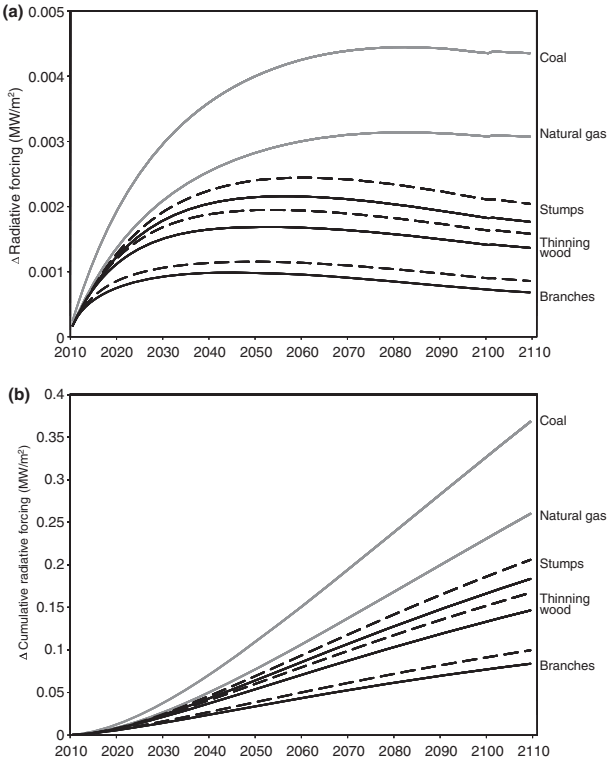

Fig. 5 The climate impact expressed as (a) instantaneous and (b) cumulative radiative forcing due to continuous energy production from different energy sources as a function of time. Each year 1 PJ of primary energy is produced from fossil fuels and Norway spruce stumps, thinning wood and branches. Forest biomass collected from Northern is indicated by dotted lines and from Southern Finland by solid lines.

CO_2 when left in forest. For the same reason, the production of bioenergy from branches caused a smaller climate impact, which furthermore leveled off sooner, compared to the bioenergy production from stumps or thinning wood that decompose at a slower rate. The decreasing trend in the instantaneous RFs results from the assumed development of background concentrations, because the higher the atmospheric concentration of a GHG is, the smaller additional RF is caused by further emissions. When expressed as the cumulative RF, the warming impact of different energy sources proceeded rather linearly, but with differing rates, for most of the calculation period, corresponding to the leveled-off instantaneous RFs (Fig. 5b).

The potential of forest bioenergy to reduce the climate impact of energy production depended on the reference period, the diameter of forest biomass and the climatic conditions at the forest residue removal site. In the short term, producing energy continuously from the spruce branches collected from Southern Finland for 20 years reduced the cumulative RF 47–62% compared to fossil fuels, whereas for the stumps the reduction was only 11–37%. In the long term (100 years), the reduction gained with the use of branches was 68–77%, and that with stumps 29–50%. When forest residues were collected from Northern Finland, the reductions in these climate impacts were up to 9 percentage units less.

Among the cases studied, the largest reduction in the climate impact of the energy production after 20 years, up to 62%, was achieved when coal was replaced by the branches collected from Southern Finland, whereas the smallest reductions 7% was gained by using stumps from Northern Finland instead of natural gas. After 100 years the corresponding values were 77% and 21%.

Discussion

The results of this study show that using forest residues for energy production is neither GHG emission free nor carbon neutral. This is mainly because the combustion of forest residues releases the carbon into the atmosphere much faster than natural decomposition of the residues. Hence, the energy use of forest residues decreases the carbon stocks of the forests and increases the atmospheric concentrations of GHGs compared to situation in which harvest residues are not used for energy (e.g. Palosuo *et al.*, 2001; Holmgren *et al.*, 2007; Kujanpää *et al.*, 2010; Walker *et al.*, 2010; Zanchi *et al.*, 2010).

The model calculations in this study show clearly that the initial increase in GHG emissions reduces the efficiency of forest bioenergy for rapid GHG emissions reduction. The total emissions and consequent RFs are highest and comparable to those of fossil fuels when bioenergy production from forest residues is started or the amount of forest residues collected from forests is increased. The GHG emissions decrease and the instantaneous RF gradually level off as bioenergy production is continued, because the forest residues would release CO_2 by decomposition even if left in the forest. Climate benefits from using forest residues for energy are only achieved in a time period over decades which is also shown in previous studies. Zetterberg *et al.* (2004) and Holmgren *et al.* (2007) concluded that the instantaneous RF due to continuous forest residue energy production is even larger than that of natural gas for the first 20 years. Zetterberg *et al.* (2004) further estimated that the cumulative RF resulting from forest residue energy use was of the same magnitude as that of fossil fuels for the first decades, whereas Savolainen *et al.* (1994) showed that it takes more than 12 years before the RF of forest residue energy use to drop below that of natural gas.

Because of the time-dependency of the GHG emissions and concentrations, the choice of time perspective critically affects the outcome of the studies on climate impacts of forest bioenergy. If the GHG emissions and climate impacts are only assessed after a fixed period of 100 years or after one forest rotation period, the effect of the timing and variation of emissions on atmospheric concentrations is ignored. In this study, this limitation is avoided by using a dynamic RF model that takes into account the year-to-year variations in both emission rates and atmospheric concentrations. The importance of considering time perspective when comparing different energy options to mitigate climate change has been stressed in earlier studies (Schlamadinger & Marland, 1996; Petersen Raymer, 2006; Holmgren *et al.*, 2007; Kirkinen *et al.*, 2008; Bird *et al.*, 2010), but there is no consensus on the time perspective that should be used (Shine, 2009). Eventually the choice of the time scale is a value-laden one (Shine, 2009), and depends on whether short- or long-term objectives are set for GHG reduction (Schlamadinger *et al.*, 1997; Kirkinen *et al.*, 2008).

The results of this study show that it is possible to improve climate impacts of bioenergy production from forest residues by allocating the forest residue removal to the quickly decomposing biomasses. In the previous studies of the forest bioenergy climate impacts (Savolainen *et al.*, 1994; Zetterberg *et al.*, 2004; Holmgren *et al.*, 2007; Kirkinen *et al.*, 2008), the decomposition of harvests residues left to the forest has been included, but the variation in the decay rate among forest residues has not been accounted for. Zetterberg *et al.* (2004) point out that assuming a slower biomass decomposition rate would result in higher global change impact than that presented in their study. The current study demonstrates that there are significant differences in emissions

and their climate impacts depending on the forest residue decomposition rate, which is mainly affected by forest residue diameter and climatic conditions of the removal site. Tree species or the harvest method of thinning wood (whole tree or stem-only) contribute less to the magnitude of the emissions and their climate impact. Using stumps from Finnish forests causes almost three times the total emissions and over two twice as large an effect on cumulative RF, compared with using branches across a time period of 100 years. Therefore, implementing national plans to increase bioenergy production may result in diverging emission reductions and climate impacts depending on which forest residues are collected for bioenergy and where the collection takes place. This issue has not yet been taken into account when planning national forest bioenergy strategies.

The reliability of the current results depend especially on the decomposition estimates, calorific values and moisture contents used, as well as variation in the chemical composition of litter. The Yasso07 model is shown to give unbiased estimates for the decomposition of woody (Tuomi *et al.*, 2011) and nonwoody litter (Tuomi *et al.*, 2009) and produce similar decomposition rate estimates with other studies under comparable conditions (Repo *et al.*, 2011), except for the late phases of decomposition for which the Yasso07 estimates are higher than those of Melin *et al.* (2009) and Palviainen *et al.* (2010). One reason for the higher estimates can be that Yasso07 model includes also the formation of slowly decomposing soil organic matter that is not accounted for in the measurements that follow mass loss. Including all carbon pools is crucial when emissions from forest bioenergy are studied. The differences in decomposition estimates between studies show that more research is needed to provide more reliable estimates on organic matter decomposition. The energy content of wood varies more according to moisture content than tree species or tree part (Alakangas, 2005). The moisture content of the wood chips used in Finland vary within 35–50% (m/m) being higher in larger power plants (Hakkila, 2004; Mäkinen *et al.*, 2006b). The variation of moisture content has been included in the uncertainty estimates in his study. According to these analyses it has a smaller effect on the forest fuel emissions than residue diameter or climatic conditions of the collection site. The chemical composition varies between tree species, tree parts and geographical locations (Voipio & Laakso, 1992; Nurmi, 1993, 1997; Alakangas, 2005). However, the availability of this detailed information in the form required to run Yasso07 model is limited. The estimates of chemical composition are based on various studies (Berg & Wessén, 1984; Berg *et al.*, 1984; Hakkila, 1989), and the uncertainty of chemical composition was included in the decomposition simulations.

In this study, over 90% of the total GHG emissions result from a decrease in forest carbon stocks. In other studies, the GHG emissions from collecting, chipping and transportation of forest residues have been estimated to be 1–3 g CO_2 eq. MJ^{-1}, depending on the operations included and the allocation principles applied (Palosuo *et al.*, 2001; Mälkki & Virtanen, 2003; Wihersaari, 2005b; Mäkinen *et al.*, 2006b; Holmgren *et al.*, 2007). These values are in accordance with the estimates obtained in this study. Including recirculation of ash and nitrogen fertilization, to compensate for the nutrient losses resulting from forest residue removal, can each increase the forest fuel chain emissions by 2 g CO_2 eq. MJ^{-1} (Wihersaari, 2005b). Still, the emissions from the forest fuel chain are relatively small compared to the emissions resulting from the decrease in carbon stocks. Therefore, significant reductions in GHG emissions from forest bioenergy are achieved by focusing on minimizing the reduction in carbon stocks.

In addition to factors considered in this study also other aspects add uncertainty to the results. The possible CO_2 emissions due to forest soil disruption associated with stump removal or potential methane emissions resulting from anaerobic degradation during forest fuel storage (Wihersaari, 2005a) were not accounted for in this study. Empirical studies on the magnitude or duration of the former emission source are few (Hope, 2007; Jandl *et al.*, 2007; Walmsley & Godbold, 2010). In a Finnish study, the site preparation increased CO_2 efflux from the soil, but this effect leveled off rapidly (Pumpanen *et al.*, 2004). However, the stump harvesting may cause deeper mixing and more extensive scarification of soil than the site preparation (Egnell *et al.*, 2007). The CO_2 efflux from a stump harvest site in Sweden was observed to be slightly larger with more seasonal variation than the efflux from a clear-cut site (SLU 2009). Therefore, stump harvesting has been suggested to increase the temperature sensitivity of decomposition and increase CO_2 effluxes in warming climate conditions (SLU 2009). According to field studies, logging residue extraction can also have a significant negative effect on future forest growth because of increased nutrient removal (Egnell, 2011; Helmisaari *et al.*, 2011). This would mean a decreased carbon stock in living biomass and a further negative effect on the GHG profile of forest residue bioenergy.

Conclusions

Producing energy from forest residues decreases GHG emissions in the long term, and thus it can serve as a means to mitigate climate change, but because of the

time-dependency of emissions, increasing bioenergy production from forest residues will not result in deep GHG emission reductions in short term. The GHG emissions and consequent climate impacts of different forest bioenergy options differ significantly. The potential of forest residue bioenergy to reduce the GHG emissions and the consequent climate impacts depends particularly on the decay rate of the forest residues collected for bioenergy. The choice of forest residues collected affects critically the magnitude and the timing of the emission reductions and climate benefits that a country can achieve with forest bioenergy.

Acknowledgements

This study was partially funded by Maj and Tor Nessling Foundation through research project 'Climate impacts of forest bioenergy', the European Commission through research project 'Greenhouse gas management in European land use systems' (grant agreement no. 244122), and Finnish Ministry of the Environment though research project 'Renewable energy sources promoted according to RES-sustainability criteria: forest bioenergy and climate impacts'. We thank Tuomas Mattila for the help with Ecoinvent database and the referees for their comments and suggestions.

References

Alakangas E (2005) *Properties of Wood Fuels Used in Finland*. VTT Processes, Project Report PRO2/P2030/05 (Project C5SU00800). VTT, Jyväskylä.

Berg B, Wessén B (1984) Changes in organic-chemical components and in growth of fungal mycelium in decomposing birch leaf litter as compared to pine needles. *Pedobiologia*, **26**, 285–298.

Berg B, Ekbohm G, McClaugherty C (1984) Lignin and holocellulose relations during long-term decomposition of some forest litters. Long-term decomposiotion in a Scots pine forest IV. *Canadian Journal of Botany-Revue Canadienne De Botanique*, **62**, 2540–2550.

Berg B, Booltink H, Braymeyer A *et al*. (1991) *Data on needle litter decomposition and soil climate as well as site characteristics for some coniferous forest sites. Part 2. Decomposition data*. Swedish University of Agricultural Sciences Report 42, Uppsala.

Beurskens L, Hekkenberg M (2011) *Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States*. Energy Research Centre of the Netherlands and European Environment Agency, the Netherlands. ECN-E-10-069 (2 January 2011).

Bird N, Cowie A, Frieden D *et al*. (2010) *Emissions from Bioenergy: Improved Accounting Options and New Policy Needs*. 18th European Biomass Conference and Exhibition, 3–7 May 2010, Lyon, France. Available at: http://www.ieabioenergy-task38.org/index.htm (accessed 21 August 2011).

BS EN 14961-1 (2010) *Solid Biofuels. Fuels Specifications and Classes. General Requirements*. BSI, London, UK.

Börjesson P (1996) Emissions of CO_2 from biomass production and transportation in agriculture and forestry. *Energy Conversion and Management*, **37**, 1235–1240.

Drebs A, Nordlund A, Karlsson P, Helminen J, Rissanen P (2002) *Climatic Statistics of Finland No. 2002:1*. Finnish Meteorological Institute, Helsinki.

Ecoinvent Centre (2007) *Ecoinvent Data v2.0*. Swiss Centre for Life Cycle Inventories, St-Gallen, Switzerland.

Egnell G, Hyvönen R, Högbom L *et al*. (2007) *Environmental aspects on stump-harvest – compilation of knowledge and knowledge gaps*. Rapport ER 2007:40 (June 2007).

Egnell G (2011) Is the productivity decline in Norway spruce following whole-tree harvesting in the final felling in boreal Sweden permanent or temporary? *Forest Ecology and Management*, **261**, 148–153.

Eriksson L, Gustavsson L (2008) Comparative analysis of wood chips and bundles – costs, carbon dioxide emissions, dry-matter losses and allergic reactions. *Biomass and Bioenergy*, **34**, 82–90.

EU Energy and Climate Package (2008) The package of EU climate and energy measures approved in December 2008. Available at: http://ec.europa.eu/clima/policies/brief/eu/package_en.htm (accessed 3 January 2011).

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

Forsberg G (2000) Biomass energy transport: analysis of bioenergy transport chains using life cycle inventory method. *Biomass and Bioenergy*, **19**, 17–30.

Hakkila P (1989) *Utilization of Residual Forest Biomass*. Springer-Verlag, Berlin.

Hakkila P (2004) *Developing technology for large-scale production of forest chips. Wood Energy Wood Energy Technology Programme 1999–2003*. Technology Programme Report, 6/2004 Final Report Helsinki.

Harmon M, Franklin J, Swanson F *et al*. (1986) Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research*, **15**, 133–302.

Harmon M, Krankina O, Sexton J (2000) Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, **30**, 76–84.

Helmisaari H-S, Hanssen K H, Jacobson S *et al*. (2011) Logging residue removal after thinning in Nordic boreal forests: long-term impact on tree growth. *Forest Ecology and Management*, **261**, 1919–1927.

Holmgren K, Eriksson E, Olsson O, Olsson M, Hillring B, Parikka M (2007) *Biofuels and climate neutrality – system analysis of production and utilisation*. Elforsk Rapport 07:35.

Hope G (2007) Changes in soil properties, tree growth, and nutrition over a period of 10 years after stump removal and scarification on moderately coarse soils in interior British Columbia. *Forest Ecology and Management*, **242**, 625–635.

IPCC (2001) *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK/New York, NY, USA.

IPCC (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK/New York, NY, USA.

Jandl R, Lindner M, Vesterdal L *et al*. (2007) How strongly can forest management influence soil carbon sequestration? *Geoderma*, **137**, 253–268.

Jylänki L (2010) *Defining the Parameters of Chips from Delimbed Stems and Comparing the Sampling Ways*. Diploma Work. Department of Forestry, Tampere University of Applied Sciences, Tampere (in Finnish).

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.

Kujanpää M, Eggers J, Verkerk H, Helin T, Lindner M, Wessman H (2010) *Carbon balance of forest residue collection and combustion in Southern Finland*. Proceeding Paper in the 18th European Biomass Conference and Exhibition, ETA-Florence Renewable Energies, Florence. OC2.4, pp. 1575–1579.

Kuusinen M, Ilvesniemi H (eds) (2008) *The Environmental Impact of Collecting Energy Wood, Research Report (In Finnish: Energiapuun korjuun ympäristövaikutukset, tutkimusraportti)*. Tapion ja Metlan Julkaisuja, Finnish Forest Research Institute, Metla and Forestry Development Centre Tapio, Helsinki, Vantaa.

Laitila J, Asikainen A, Anttila P (2008) 1. Energiapuuvarat. In: *Energiapuun korjuun ympäristövaikutukset, tutkimusraportti* (eds Kuusinen M, Ilvesniemi H), pp. 6–12. Tapion ja Metlan Julkaisuja, Finnish Forest Research Institute, Metla and Forestry Development Centre Tapio, Helsinki, Vantaa, Finland.

Lipasto/LIISA (2009) Unit emissions of vehicles in Finland. Available at: http://lipasto.vtt.fi/yksikkopaastot/tavaraliikennee/tieliikennee/tavara_tiee.htm (accessed 21 August 2011).

Lipasto/TYKO (2009) Calculation model for working machines 2008. Available at: http://lipasto.vtt.fi/tyko/mallie.htm (accessed 21 August 2011).

Liski J, Ilvesniemi H, Makela A, Starr M (1998) Model analysis of the effects of soil age, fires and harvesting on the carbon storage of boreal forest soils. *European Journal of Soil Science*, **49**, 407–416.

Liski J, Westman CJ (1995) Density of organic-carbon in soil at coniferous forest sites in Southern Finland. *Biogeochemistry*, **29**, 183–197.

Liski J, Westman CJ (1997) Carbon storage in forest soil of Finland. 2. Size and regional patterns. *Biogeochemistry*, **36**, 261–274.

Lohila A, Minkkinen K, Laine J *et al*. (2010) Forestation of boreal peatlands: impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *Journal of Geophysical Research*, **115**, G04011.

Melillo JM, Reilly JM, Kicklighter DW *et al*. (2009) Indirect emissions from biofuels: how important? *Science*, **326**, 1397–1399.

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.

Melin Y, Petersson H, Nordfjell T (2009) Decomposition of stump and root systems of Norway spruce in Sweden – a modelling approach. *Forest Ecology and Management*, **257**, 1445–1451.

Ministry of Employment and the Economy of Finland (2008) *National long-term climate and energy strategy of Finland*. Government Report to Parliament (6 November 2008) (in Finnish).

Ministry of Employment and the Economy of Finland (2010) *Finland's national action plan for promoting energy from renewable sources pursuant to Directive 2009/28/EC* (30 June 2010).

Monni S, Korhonen R, Savolainen I (2003) Radiative forcing due to anthropogenic greenhouse gas emissions from Finland: methods for estimating forcing of a country or an activity. *Environmental Management*, **31**, 401–411.

Mäkinen H, Hynynen J, Siitonen J, Sievanen R (2006a) Predicting the decomposition of Scots pine, Norway spruce, and Birch stems in Finland. *Ecological Applications*, **16**, 1865–1879.

Mäkinen T, Soimakallio S, Paappanen T, Pahkala K, Mikkola H (2006b) Liikenteen biopolttoaineiden ja peltoenergian kasvihuonekaasutaseet ja uudet liiketoimintakonseptit [Greenhouse gas balances and new business opportunities for biomass-based transportation fuels and agrobiomass in Finland]. VTT Tiedotteita. VTT Research Notes 2357. VTT, Espoo (in Finnish).

Mälkki H, Virtanen Y (2003) Selected emissions and efficiencies of energy systems based on logging and sawmill residues. *Biomass and Bioenergy*, **24**, 321–327.

Nurmi J (1993) Heating values of the above ground biomass of small-sized trees. *Acta Forestalia Fennica*, **236**, 30.

Nurmi J (1997) Heating values of mature trees. *Acta Forestalia Fennica*, **256**, 28.

Palosuo T, Wihersaari M, Liski J (2001) Net greenhouse gas emissions due to energy use of forest residues – impact of soil carbon balance. EFI Proceedings No. 39. In: *Wood Biomass as an Energy Source Challange in Europe* (eds Pelkonen P, Hakkila P, Karjalainen T, Schlamadinger B), pp. 115–130. European Forest Institute, Joensuu.

Palviainen M, Finér L, Laiho R, Shorohova E, Kapitsa E, Vanha-Majamaa I (2010) Carbon and nitrogen release from decomposing Scots pine, Norway spruce and silver birch stumps. *Forest Ecology and Management*, **259**, 390–398.

Palviainen M, Laiho R, Mäkinen H, Finér L (2008) Do decomposing Scots pine, Norway spruce, and silver birch stems retain nitrogen? *Canadian Journal of Forest Research*, **38**, 3047–3055.

Petersen Raymer AK (2006) A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy*, **30**, 605–617.

Pumpanen J, Westman CJ, Ilvesniemi H (2004) Soil CO_2 efflux from a podzolic forest soil before and after forest clear-cutting and site preparation. *Boreal Environment Research*, **9**, 199–212.

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.

Savolainen I, Hillebrand K, Nousiainen I, Sinisalo J (1994) *Comparison of Radiative Forcing Impacts of the Use of Wood, Peat, and Fossil Fuels*. VTT Tiedotteita – VTT Research Notes 1559. VTT, Jyväskylä.

Schlamadinger B, Apps M, Bohlin F *et al*. (1997) Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. *Biomass and Bioenergy*, **13**, 359–375.

Schlamadinger B, Marland G (1996) Full fuel cycle carbon balances of bioenergy and forestry options. *Energy Conversion and Management*, **37**, 813–818.

Schlamadinger B, Spitzer J, Kohlmaier GH, Lüdeke M (1995) Carbon balance of bioenergy from logging residues. *Biomass and Bioenergy*, **8**, 221–234.

Searchinger T, Heimlich R, Houghton RA *et al*. (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.

Searchinger TD, Hamburg SP, Melillo J *et al*. (2009) Fixing a critical climate accounting error. *Science*, **326**, 527–528.

Shine K (2009) The global warming potential – the need for an interdisciplinary retrial. *Climatic Change*, **96**, 467–472.

Shine K, Cook J, Highwood E, Joshi M (2003) An alternative to radiative forcing for estimating the relative importance of climate change mechanisms. *Geophysical Research Letters*, **30**, 2047.

SLU (2009) *Stubbskörd och miljöeffekter – TEMA stubbar – Årsrapport för 2009 [Stump harvesting and environmental effects – year report 2009]*. SLU – Swedish University of Agricultural Sciences, Uppsala (in Swedish).

Statistics Finland (2011) *Fuel Classification (1 January 2011)*. Statistics Finland, Helsinki.

Stupak I, Asikainen A, Jonsell M *et al*. (2007) Sustainable utilisation of forest biomass for energy-possibilities and problems: policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. *Biomass & Bioenergy*, **31**, 666–684.

Tarasov ME, Birdsey RA (2001) Decay rate and potential storage of coarse woody debris in the Leningrad Region. *Ecological Bulletin*, **49**, 137–147.

Tsupari E, Tormonen K, Monni S, Vahlman T, Kolsi A, Linna V (2006) *Emission factors for nitrous oxide (N_2O) and methane (CH_4) from Finnish power and heating plants and small-scale combustion*. VTT Working Papers 43, VTT, Espoo.

Tuomi M, Laiho R, Repo A, Liski J (2011) Wood decomposition model for boreal forests. *Ecological Modelling*, **222**, 709–718.

Tuomi M, Thum T, Järvinen H *et al*. (2009) Leaf litter decomposition – estimates of global variability based on Yasso07 model. *Ecological Modelling*, **220**, 3362–3371.

Walker T, Cardellichio P, Colnes A *et al*. (2010) *Biomass Sustainability and Carbon Policy Study*. NCI-2010-03 (June 2010). Manomet Center for Conservation Sciences, Massachusetts.

Walmsley J, Godbold D (2010) Stump harvesting for bioenergy – a review of the environmental impacts. *Forestry*, **83**, 17–38.

Vávrová P, Penttilä T, Laiho R (2009) Decomposition of Scots pine fine woody debris in boreal conditions: implications for estimating carbon pools and fluxes. *Forest Ecology and Management*, **257**, 401–412.

Wihersaari M (2005a) Evaluation of greenhouse gas emission risks from storage of wood residue. *Biomass & Bioenergy*, **28**, 444–453.

Wihersaari M (2005b) Greenhouse gas emissions from final harvest fuel chip production in Finland. *Biomass & Bioenergy*, **28**, 435–443.

Voipio R, Laakso T (1992) Pienikokoisten puiden maanpäällisen biomassan kemiallinen koostumus [Chemical composition of the above ground biomass of small-sized trees]. *Folia Forestalia*, **789**, 22 (in Finnish with English summary).

Zanchi G, Pena N, Bird N (2010) *The Upfront Carbon Dept of Bioenergy*. Joanneum Research, Graz.

Zetterberg L, Uppenberg S, Åhman M (2004) Climate impact from peat utilisation in Sweden. *Mitigation and Adaptation Strategies for Global Change*, **9**, 37–76.

Äijälä O, Kuusinen M, Koistinen A (eds) (2010) *Hyvän metsänhoidon suositukset energiapuun korjuu ja kasvatus [The good practice guidance to energy wood collection and growing]*. Metsätalouden kehittämiskeskus Tapion julkaisuja. Forestry Development Centre Tapio, Helsinki (in Finnish).