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Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues

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Abstract

Forest harvest residues are important raw materials for bioenergy in regions practicing forestry. Removing these residues from a harvest site reduces the carbon stock of the forest compared with conventional stem-only harvest because less litter in left on the site. The indirect carbon dioxide (CO_2) emission from producing bioenergy occur when carbon in the logging residues is emitted into the atmosphere at once through combustion, instead of being released little by little as a result of decomposition at the harvest sites. In this study (1) we introduce an approach to calculate this indirect emission from using logging residues for bioenergy production, and (2) estimate this emission at a typical target of harvest residue removal, i.e. boreal Norway spruce forest in Finland. The removal of stumps caused a larger indirect emission per unit of energy produced than the removal of branches because of a lower decomposition rate of the stumps. The indirect emission per unit of energy produced decreased with time since starting to collect the harvest residues as a result of decomposition at older harvest sites. During the 100 years of conducting this practice, the indirect emission from average-sized branches (diameter 2 cm) decreased from 340 to 70 kg CO_2 eq. MWh^{-1} and that from stumps (diameter 26 cm) from 340 to 160 kg CO_2 eq. MWh^{-1}. These emissions are an order of magnitude larger than the other emissions (collecting, transporting, etc.) from the bioenergy production chain. When the bioenergy production was started, the total emissions were comparable to fossil fuels. The practice had to be carried out for 22 (stumps) or four (branches) years until the total emissions dropped below the emissions of natural gas. Our results emphasize the importance of accounting for land-use-related indirect emissions to correctly estimate the efficiency of bioenergy in reducing CO_2 emission into the atmosphere.

Keywords: bioenergy, forest harvest residue, indirect emissions, land use, soil carbon, Yasso07

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Introduction

Bioenergy, i.e. energy derived from renewable biomass, is used to replace fossil fuels in energy production in order to decrease greenhouse gas emissions into the atmosphere. The rationale behind this practice is that bioenergy does not cause any net carbon dioxide (CO_2) emissions since the amount of CO_2 released into the atmosphere in combustion is taken up again by the next generation of growing plants (Wihersaari, 2005; Stupak *et al*., 2007; Lattimore *et al*., 2009).

Following this idea, as a means to cut down greenhouse gas emissions, the Council of the European Union (EU) adopted a directive on the promotion of renewable energy, including bioenergy. This directive set targets to produce 20% of the final energy consumption using renewable energy sources in the EU by the year 2020. This target is higher for member states already producing a lot of renewable energy, for example as a by-product of pulping industry. Consequently, the national commitment is 38% for Finland and 49% for Sweden (Directive 2009/28/EC). During the reference year of the directive 2005, renewable sources represented already 28% of the total energy production in Finland and 39% in Sweden, while the EU-average was 11%.

These high targets for renewable energy are increasing the focus on biomass for energy production. Worldwide, this growing interest in bioenergy puts pressure

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on land use changes, including deforestation and consequent conversion of the forest land to energy crop cultivation (Melillo *et al*., 2009).

Recently, indirect CO_2 emissions from bioenergy production associated with these land use changes have caused concern (Searchinger *et al*., 2008, 2009; Melillo *et al*., 2009). These indirect emissions occur when bioenergy production reduces the carbon stocks of biomass or soil. These carbon losses may be remarkable, and it is even possible that replacing fossil fuels with bioenergy increases net greenhouse gas emissions into the atmosphere as a consequence of large indirect emissions. The assumed CO_2 neutrality of biofuels like ethanol and their actual potential to mitigate climate change have already been questioned because of large negative impacts on the carbon stock of soil (Fargione *et al*., 2008; Searchinger *et al*., 2008, 2009; Melillo *et al*., 2009).

It is important to realize that the indirect emissions of bioenergy production are not limited to the cases of land use change but may also be caused by new practices of ecosystem management within the same land use. In countries with extensive forest cover and an already high share of renewable energy, an appealing way to produce bioenergy is to intensify biomass removals from forests. Forested countries Finland and Sweden are pioneers in the field of using forest residues for energy production (Mälkki & Virtanen, 2003). Still, in order to meet the EU commitment of renewable energy, Finland plans to increase the use of logging residues for energy production from $3.6\,\mathrm{Mm^3\,yr^{-1}}$ in 2006 to $12\,\mathrm{Mm^3\,yr^{-1}}$ by 2020 (Ministry of Employment and the Economy of Finland, 2008).

Until now, research on the effects of logging residue removal has focused on nutrient balances (e.g. Wall, 2008; Luiro *et al*., 2009), socioeconomic impacts (e.g. Börjesson, 2000), profitability (e.g. Heikkilä *et al*., 2007), forest productivity (e.g. Peng *et al*., 2002) and properties of wood fuel (e.g. Alakangas, 2005), whereas the indirect emissions have received little attention. Lattimore *et al*. (2009) dealt with the indirect emissions to some extent in their recent review. They concluded that, in order to be sustainable, bioenergy production from forest residues must not have adverse effects on soil quality, hydrology and water quality, site productivity, or forest biodiversity but also not on greenhouse gas balances.

The indirect emissions from removing forest harvest residues, and using them for energy production, result from combusting the residues and releasing CO_2 into the atmosphere soon after harvesting instead of letting them decompose slowly at the harvested site. As a consequence of such practice, the amount of carbon stored at the forest site decreases, possibly to a remarkable degree.

There are some field studies (Johnson *et al*., 2002; Jones *et al*., 2008) and model-based calculations (Palosuo *et al*., 2001; Peng *et al*., 2002; Ågren & Hyvönen, 2003; Eriksson *et al*., 2007) regarding the effect of logging residue removal on the carbon stock of soil. Some of these studies show clearly that intensified removal of harvest residues reduces the soil carbon stock (Johnson & Curtis, 2001; Ågren & Hyvönen, 2003; Eriksson *et al*., 2007). Palosuo *et al*. (2001) estimated that the indirect emissions from decreasing carbon stock are an order of magnitude larger than the other emissions from an energy production chain utilizing forest harvest residues. Despite the significant contribution of indirect emissions to the estimate of total emissions per unit of produced energy, Palosuo *et al*. (2001) calculate emissions of approximately $50\,\mathrm{kg\,CO_2\,eq.\,MWh^{-1}}$, which is 80–90% less than the emissions from various fossil fuels.

The indirect emission of using logging residues for energy production depend critically on the decomposition rate of the residues if they were left at the site. Studies based on extensive sets of measurements have been published recently making it possible to estimate the decomposition rate of the harvest residues more reliably than before (e.g. Tarasov & Birdsey, 2001; Palviainen *et al*., 2004; Mäkinen *et al*., 2006; Vávřová *et al*., 2009). We have used these measurements plus other measurements related to decomposition and carbon cycling in soil and developed a new soil carbon model Yasso07 (Tuomi *et al*., 2008, 2009). The large datasets used and advanced mathematical methods applied make the Yasso07 model particularly suitable for estimating the decomposition rate of woody litter in boreal forests.

In this study, we used this model to estimate the indirect emissions from using logging residues for bioenergy production. The objectives of the current study were to (1) introduce an approach to estimate the indirect CO_2 emissions associated with bioenergy production from forest harvest residues, (2) estimate these emissions in a forested boreal landscape during the first 100 years after starting to produce bioenergy from harvest residues, and (3) compare the total CO_2 emissions per unit of bioenergy produced to the emissions caused by using other fuels.

Materials and methods

Modelling decomposition of forest harvest residues

To estimate the indirect CO_2 emissions from producing bioenergy from forest harvest residues in boreal conditions, we simulated the decomposition of logging residues using a user-interface of the dynamic soil carbon model Yasso07 (Tuomi *et al.*, 2008, 2009, http://www.environment.fi/syke/yasso). The measurements of the decomposition of woody litter used to develop the model were taken in Finland and neighboring regions in Estonia and Russia (M. Tuomi, R. Laiho, A. Repo & J. Liski, unpublished results). These measurements used represent the majority of data on woody litter decomposition in this region. The data sets includes branches and stems ranging from 0.5 to 60 cm in diameter, and the mass loss of these woody biomass components has been followed for 1–70 years since the start of decomposition. In addition to these data, the Yasso07 model is based on an extensive data set on decomposition of nonwoody litter across Europe and North and Central America (Tuomi *et al.*, 2009) plus data sets on the accumulation and stock of soil organic carbon (Liski & Westman, 1995, 1997; Liski *et al.*, 1998). These additional measurements specially provide information on the cycling of recalcitrant organic carbon compounds in soil that are relevant for the long-term carbon balance of decomposing woody litter.

The parameter values of Yasso07 have been sampled using a Markov chain Monte Carlo method (Tuomi *et al.*, 2009). This method has been used to make sure that, first, the model is not over-parameterized given the data and, second, there are unequivocal maximum likelihood values for each parameter combination. This mathematical approach and the data available in the development process of Yasso07 make this model suitable for this study because the uncertainty estimates of the model predictions are available and because the data covers the simulated scenarios well without extrapolation.

Model simulations

Using Yasso07, we simulated the decomposition of harvest residues at a typical site of harvest residue removal in Finland, namely an even-aged mature 81–100-year-old Norway spruce (*Picea abies* L.) forest stand located in the Pirkanmaa region of Southern Finland. Spruce stands cover some 40% of forest area in this region (Korhonen *et al.*, 2000). Clear-cut spruce stands are favorable targets of harvest residue removals because there are more logging residues than in clear-cut Scots pine stands, which are also common in the region. Spruce stumps are also preferred over pine stumps because they are easier to extract from the soil because of a shallower root structure (Alakangas, 2005; Wihersaari, 2005).

To illustrate differences in decomposition rate between different harvest residues, we simulated decomposition of spruce branches varying from 1 to 5 cm in diameter and stumps varying from 10 to 35 cm in diameter for a 100-year period after the start of decomposition. The mean diameters of spruce branches and stems in the study region, 2 and 26 cm, respectively (Korhonen *et al.*, 2000; Kantola *et al.*, 2007), were chosen for more detailed analyses of the indirect emissions caused by using the logging residues for bioenergy production. The other input variables of the Yasso07 model used in the simulations are shown in Table 1. When estimating the indirect emissions we assumed that needles were left at the site and only branches or stumps were removed. We assumed also that there was little or no delay in combusting the harvest residues at a power plant and thus CO_2 was released to the atmosphere at once.

Energy production estimation

The indirect CO_2 emissions from using the harvest residues for bioenergy production were taken to be equal to amount of carbon remaining in the harvest residues if the residues were left to decompose at the site harvested. These emissions were also related to the amount of bioenergy produced. The cumulative indirect emissions caused by combusting the harvest residues until year *i* were calculated by summing up the amounts of carbon left in the harvest residues until this year (*i*) and relating these emissions to the cumulative amount of bioenergy produced. In other words, we

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

Climate variables	
Mean annual temperature	3.2 °C
Temperature amplitude	11.6 °C
Precipitation	681 mm
Chemical composition of woody litter	**Branch ± SD/stump ± SD (%)**
Acid hydrolysable compounds	59 ± 4.3/70 ± 5.0
Water soluble compounds	1 ± 0.3/1 ± 0.2
Ethanol soluble compounds	1 ± 0.3/1 ± 0.2
Klason lignin (neither hydrolysable nor soluble compounds)	37 ± 1.0/28 ± 0.8

The climate values represent averages for southern Finland between 1971 and 2000 (Drebs *et al.*, 2002) and the chemical composition averages of several individual studies (Hakkila, 1989). The standard deviation (SD) values of the chemical composition are based on coefficients of variation calculated from a data base of foliage litter (Berg *et al.*, 1991). The temperature amplitude means a half of the difference between the mean temperatures of the warmest and the coldest month of the year.

simulated a case where the practice of removing the harvest residues and using them for bioenergy production was started and continued on a harvest area of similar size year after year. We applied biomass-compartment-specific net calorific heating values to estimate the amount of energy obtained by combusting the harvest residues, i.e. 19.30 MJ kg^{-1} for dry Norway spruce branches and 19.18 MJ kg^{-1} for dry stumps (Nurmi, 1997). These values of dry logging residues range commonly from 18 to 20 MJ kg^{-1} (Alakangas, 2005). The carbon content of the harvest residues was assumed to be equal to 50% of dry wood (m/m).

In order to estimate the full fuel cycle emissions from using the logging residues for energy production, we added other emissions from a typical wood chip fuel production chain using harvest residues to the calculated indirect emissions. These emissions result from (1) collecting, chipping, and transporting the harvest residues, (2) emitting methane (CH_4) and nitrous oxide (N_2O) from combustion, (3) fertilizing the forest to compensate for nutrient loss, and (4) recycling ash, and they range typically from 5 to 18 kg CO_2 eq. MWh^{-1} produced (Palosuo *et al.*, 2001; Wihersaari, 2005). We used a central value of this range, 12 kg CO_2 eq. MWh^{-1} produced, in our calculations. Other estimates for direct emissions from wood fuel chain range from 5 to 20 kg CO_2 eq. MWh^{-1} (Korpilahti, 1998; Mälkki & Virtanen, 2003; Berg, 2010) depending on background information and included operations in the estimates. Fossil fuel comparison values 280, 306, and 395 kg CO_2 eq. MWh^{-1} were estimates of entire fuel cycle emissions of natural gas, oil, and diesel, and coal (Statistics Finland, 2006; Ecoinvent Centre, 2007).

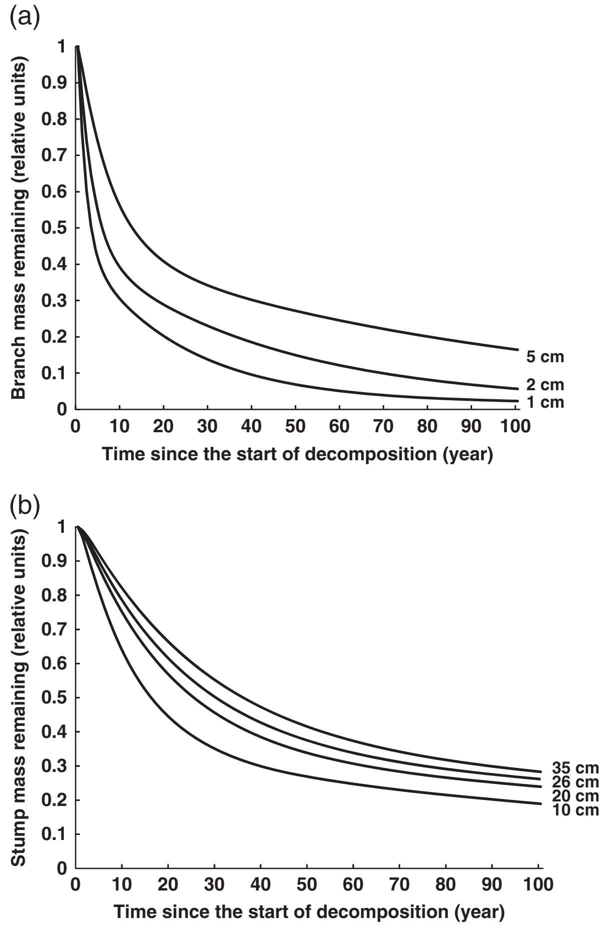

Fig. 1 Mass remaining of decomposing Norway spruce branches (diameter 1–5 cm) and stumps (diameter 10–35 cm) over a 100-year period after the start of decomposition in southern boreal conditions as simulated using the Yasso07 model (model input values in Table 1).

Results

Branches lost mass at a remarkably higher rate than stumps because the simulated decomposition rate of woody litter was dependent on the initial diameter (Fig. 1). For example, after 10 years of decomposition, the branches 1–5 cm in diameter had 30–55% of the initial mass still remaining (Fig. 1a) while stumps 10–35 cm in diameter had 63–81% (Fig. 1b). The simulated rate of mass loss decreased over time, and after 100 years of decomposition there was still 2–16% of the initial branch mass remaining and 19–28% of the initial stump mass remaining.

The indirect CO_2 emissions, caused by combusting logging residues after harvesting instead of letting them decompose at the harvested site, were equal to the CO_2 emissions from combustion, 340 kg CO_2 MWh^{-1}, when the practice was started but these emissions decreased over time as a result of decomposition of the harvest residues (Fig. 2). The indirect emissions of using branches for bioenergy decreased faster than the emissions of using stumps because the branches decomposed faster (Figs 1 and 2). After the first 10 years of conducting this practice, the indirect emissions from branches were equal to 200 kg CO_2 MWh^{-1} and those from stumps 310 kg CO_2 MWh^{-1} (Fig. 2). After the first 100 years, these emissions from the branches and stumps were equal to 70 and 160 kg CO_2 MWh^{-1}, respectively.

The estimated greenhouse gas emissions from the rest of the bioenergy production chain, i.e. the emissions from collecting, transporting, chipping, and combusting the harvest residues plus the emissions from fertilizing the forest and recycling the ash, were equal to 12 kg CO_2 eq. MWh^{-1} (Fig. 3). At the time of starting this practice, these direct emissions represented only 3% of the total emissions caused by using the harvest residues

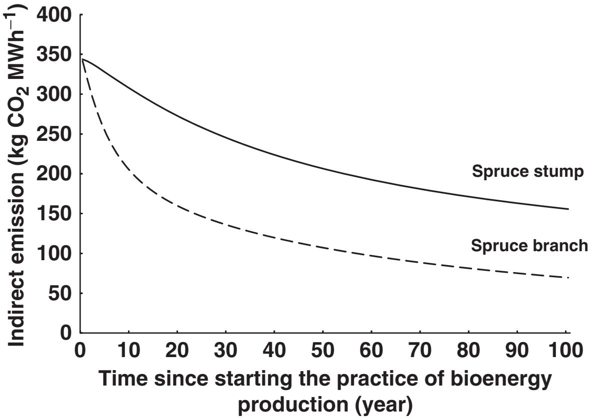

Fig. 2 Indirect CO_2 emission per unit of energy produced from using Norway spruce stumps (diameter 26 cm) or branches (diameter 2 cm) for bioenergy over a 100-year period after starting this practice. This indirect emission is equal to the carbon stock of woody litter lost in combustion per energy obtained until each year.

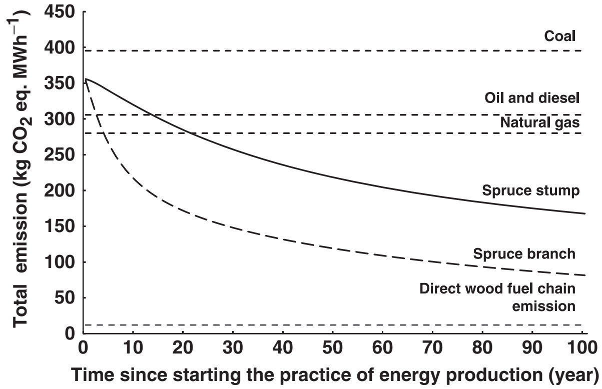

Fig. 3 The total greenhouse gas emission per unit of energy produced from using Norway spruce branches (diameter 2 cm) or stumps (diameter 26 cm) for bioenergy over a 100-year period after starting this practice and the total emissions from various fossil fuels. The emission estimates of bioenergy production include both an indirect (see Fig. 2) emission resulting from decreasing carbon stock and a direct wood fuel chain emission (equal to 12 kg CO_2 eq. MW h^{-1}) resulting from collecting, chipping and transporting the harvest residues, CH_4 and N_2O emissions from combusting the residues, fertilizing the forest to compensate for nutrient loss, and recycling of ash. The estimates of the fossil fuels represent entire fuel cycle emissions (Statistics Finland, 2006; Ecoinvent Centre, 2007).

for bioenergy. After the 100-year period of conducting this practice, this share increased to 15% if bioenergy was produced from branches and to 7% if bioenergy was produced from stumps (Fig. 3). The increased contribution of the direct emissions was a result of the decreased indirect emissions (Fig. 2).

At the time of starting to use the harvest residues for energy production, the total emissions were comparable to the emissions caused by using fossil fuels (Fig. 3). After 10 years of producing bioenergy from branches, the total emissions caused were 210 kg CO_2 eq. MWh^{-1}. These emissions are 24%, 30%, or 46% lower than the emissions caused by producing the energy from natural gas, oil, or coal, respectively. If bioenergy was produced from stumps, it took 22 years for the average emissions to decrease below the emissions of producing the energy from natural gas or 14 years for the emissions to decrease below the emissions of oil. After 100 years of producing energy by combusting branches, the emissions were lower by 71%, 74%, or 79% than the emissions caused by producing the energy from natural gas, oil, or coal, respectively. For bioenergy produced by combusting stumps, these percentages of emission reductions were 40%, 46%, or 58%, over 100 years, compared with the emissions of natural gas, oil, or coal, respectively.

Discussion

Using logging residues for energy production decreases the amount of carbon stored in forest and causes thus indirect CO_2 emissions into the atmosphere. These indirect emissions occur because combustion releases carbon of logging residues to the atmosphere at once, otherwise the residues would form a slowly decomposing carbon stock at the harvest site. The indirect emissions are an order of magnitude larger than the direct emissions from the rest of this bioenergy production chain (Fig. 3), not accounting for the CO_2 emissions of combusting the harvest residues. The indirect emissions depend on the decomposition rate of the harvest residues, with the decomposition rate being lower with an increasing size of woody litter (Fig. 1, Harmon *et al*., 1986; Janisch *et al*., 2009; M. Tuomi, R. Laiho, A. Repo & J. Liski, unpublished results). The use of bigger-sized stumps for energy production causes therefore larger indirect emissions than the use of smaller-sized branches (Fig. 2). The average indirect emissions per unit of energy produced decrease over time since the start of this form of bioenergy production (Fig. 2) but during the first few years, or a couple of decades in the case of stumps, the total emissions caused by energy production from harvest residues are comparable to the emissions of fossil fuels (Fig. 3).

The reliability of the current results depends critically on the decomposition estimates of the harvest residues. The Yasso07 decomposition and soil carbon model used in this study is based on a large collection of mass loss measurements taken on woody litter in boreal forests across Finland and neighboring countries plus large sets of other relevant measurements from across the world (see 'Materials and methods'). This model has been shown to give unbiased estimates for the decomposition of woody (M. Tuomi, R. Laiho, A. Repo & J. Liski, unpublished results) and nonwoody litter (Tuomi *et al*., 2009). Compared with other studies on the decomposition of woody litter carried out under comparable conditions, the estimates of this study are similar except for the end of the 100-year study period; for this late phase of decomposition, the current estimates of mass remaining are higher. Mäkinen *et al*. (2006) estimated that Norway spruce stems lost about 20% of their initial mass during the first 10 years of decomposition and the stems disappeared completely in some 60–80 years of time. On the other hand, according to the residuals reported by Mäkinen *et al*. (2006), their model seems to underestimate the mass remaining after 30 years of decomposition. Melin *et al*. (2009) compared several decomposition models developed for Norway spruce logs, snags, and stumps. They concluded that after 10 years of decomposition some 60–75% of the initial mass was still remaining whereas after 100 years of decomposition practically none or $<10\%$ of the initial mass was still left. Our higher estimates of mass remaining during the late phases of decomposition can be explained by a difference between the methods used. The two earlier studies were based on measurements of woody litter mass remaining. These measurements may not capture the formation and translocation of well-decayed soil organic matter originating from woody litter. The Yasso07 model, on the other hand, is additionally based on measurements of formation of soil organic matter (Tuomi *et al*., 2009). For this reason, we think that the estimates of Yasso07 model are probably more realistic for the late phases of woody litter decomposition.

In addition to the decomposition estimates, the reliability of the current results depends also on the other parameters of our calculations such as the reference energy systems or combustion techniques chosen as well as variation in the chemical composition of litter (affecting the decomposition rate estimates of the harvest residues) and calorific values. Furthermore, the simulations were done for climate conditions prevailing in Southern Finland today. The results do not thus account for the effects of climate change or those of increased atmospheric CO_2 concentration on forest growth. In addition, forest soil disruption associated with stump removal may release additional CO_2 into the atmosphere. Currently, empirical research on the magnitude of these emissions is few in number (Jandl *et al*., 2007; Walmsley & Godbold, 2010). Hope (2007) found that stump removal together with forest floor scarification reduced soil carbon stocks in the first year of stump harvesting and 9 years later. This conclusion is apparent only if during stump removal the forest soil is completely scarified by removal or mixing with mineral soil. Although the quantitative data on stump extraction and emissions associated with this practice is scarce, generally it is known that soil disturbance can change the microclimate and stimulate the decomposition of litter (Johansson, 1994). In a Finnish study site preparation after a clear-cut with mixing organic matter with mineral soil increased CO_2 efflux from soil but this effect leveled off rapidly (Pumpanen *et al*., 2004). Despite of these uncertainties, we think that the current estimates are reliable enough to demonstrate the magnitude of indirect emissions associated with producing bioenergy from harvest residues in boreal coniferous forest.

The indirect emissions, caused by the reduced carbon stock of decomposing harvest residues, represented 85–97% of the total emissions of this bioenergy production chain, not accounting for the CO_2 emissions from combusting the harvest residues. These emissions are thus highly significant for the full fuel cycle emissions of logging residues. When comparing the present results to earlier ones it is important to acknowledge differences in system boundaries, energy use-technology, reference energy system, conversion technology and type and management of raw material (Cherubini *et al*., 2009). Still, it is possible to conclude that a common outcome of the earlier studies is that the greenhouse gas emissions from logging, collecting, chipping, and transporting harvest residues are relatively low (Börjesson, 1996; Palosuo *et al*., 2001; Mälkki & Virtanen, 2003; Wihersaari, 2005). These estimates have ranged from 4 to $20\,kg\,CO_2\,MWh^{-1}$ depending on the details of the bioenergy production chains studied. The current study shows that if indirect CO_2 emissions are accounted for, the total CO_2 emissions are at least an order of magnitude higher than these emissions which have been considered to represent the total emissions (cf. Mälkki & Virtanen, 2003).

The decreasing effect of logging residue removal on soil carbon stock has been demonstrated earlier but this has not been considered to be problematic as long as this removal practice does not jeopardize the carbon sink of soil (Börjesson, 2000; Ågren & Hyvönen, 2003; Mälkki & Virtanen, 2003; Petersen Raymer, 2006; Eriksson *et al*., 2007; Sievänen *et al*., 2007; Eriksson & Gustavsson, 2008). Sievänen *et al*. (2007) calculated that increasing the removals of logging residues from 4 to $15\,Mm^3\,yr^{-1}$ in Finland will not turn the Finnish forests from net carbon sinks to net sources. However, the intensified removals of the logging residues would decrease the annual carbon sink of these forest soils by 3.1 million tons of CO_2 eq. (Sievänen *et al*., 2007). Assuming that $1\,m^3$ of harvest residues gives 2 MWh of energy (Alakangas, 2005), the indirect emission from the decreasing carbon stock of soil is equal to about 100 kg CO_2 eq. MWh^{-1}. This estimate is somewhat lower than the estimates of the present study because Sievänen *et al.* (2007) applied an earlier version of Yasso soil carbon and decomposition model in their study (Liski *et al.*, 2005). This earlier model version gave less reliable, higher estimates for the decomposition rate of woody litter because it was based on a substantially smaller number of measurements. Nevertheless, these figures demonstrate that it is important to relate the indirect and direct emissions of bioenergy production to the amount of energy obtained in order to get a correct picture on the efficiency of using different energy sources in decreasing greenhouse gas emissions to the atmosphere. The current results demonstrate that if the indirect CO_2 emissions are counted in, the total fuel chain emissions from using spruce branches or stumps for energy production may cause even bigger CO_2 emissions during the first years or decades of starting this practice than producing energy from oil or natural gas.

The indirect greenhouse gas emissions resulting from using logging residue for bioenergy production are highest per unit of energy produced immediately when the practice is started. The average emissions per energy unit decrease, however, over time. As a result of this temporal pattern, this form of bioenergy production is not efficient in decreasing emissions to the atmosphere in the near future. Our results stress the importance of considering time perspective when assessing the potential of different bioenergy options to mitigate climate change (Schlamadinger & Marland, 1996; Petersen Raymer, 2006). The issue of which temporal approach is appropriate depends on the management and policy strategies and whether the selection of energy systems is made to meet long-term or short-term greenhouse gas reduction objectives (Schlamadinger *et al.*, 1997).

It is possible to reduce the indirect emissions of logging residue removals by collecting quickly decomposing harvest residues for bioenergy production, for example branches instead of stumps. However, it may be still tempting to extract stumps from harvest sites because the gain of primary energy per hectare may be twice that compared with collecting branches (Eriksson & Gustavsson, 2008). Leaving the needles at the harvest site, which helps to avoid nutrient loss, has a marginal effect on the carbon balance at clear-cut sites, although needle and fine root litter produce more than two-thirds of the soil carbon stock in growing forests (Ågren & Hyvönen, 2003).

The indirect emissions have a remarkable effect on the total greenhouse gas emissions from some systems of bioenergy production, as demonstrated in this study for harvest residues of boreal forests, and emphasized for several other systems by Johnson (2009) and Searchinger *et al.* (2009). For this reason, to account for the actual greenhouse gas effect of various alternative bioenergy options, it would be essential to include the indirect emissions adequately in guidelines of greenhouse gas inventorying and reporting. Currently, the rules of carbon accounting applied under the Kyoto Protocol do not count all indirect emissions, which among other things distorts the accounting of net emissions (Johnson, 2009; Searchinger *et al.*, 2009). A particular shortcoming of the accounting rules under the Kyoto Protocol is that a party to this protocol may choose not to account for changes in one or several of the agreed carbon pools (aboveground biomass, belowground biomass, litter, dead wood, and soil organic carbon) as long as it can reliably show that the pool is not decreasing. Owing to this threshold, some of the indirect emissions caused by using logging residues for bioenergy production may be excluded from the inventory figures. On the other hand, in inventory reports of greenhouse gases under the United Nations Framework Convention on Climate Change, the carbon release resulting from forest harvesting must be counted and reported as a land-use emission or as a energy emission but not both (IPCC, 2000). Today, the land-use-related greenhouse gas emissions from bioenergy production systems are recognized and investigated (IPCC, 2000; Melillo *et al.*, 2009) but one of the practical problems is that measuring methods for the indirect effects and feasible means to bring these impacts to regulatory policies are still lacking (Mathews & Tan, 2009).

Conclusions

Using logging residues as a source of bioenergy causes net CO_2 emissions into the atmosphere and a great majority (85–97%) of these emissions are indirect emissions resulting from a decline in the carbon stock of harvest residues in forest. The amount of the indirect emissions increases with a decreasing decomposition rate of the harvest residues. Norway spruce stumps decay at slower rate than branches and consequently the energy use of the stumps causes 1.5–2 times larger indirect emissions than the use of branches. Production of bioenergy from forest harvest residues causes emissions that are comparable to the emissions of fossil fuel over the first few years (branches) or first few decades (stumps) of the practice. After 50 years, bioenergy produced of Norway spruce stumps decreases average emissions per unit of energy produced by some 20% and bioenergy from branches by some 60% compared with entire fuel cycle emissions of natural gas.

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