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Can we produce carbon and climate neutral forest bioenergy?

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Abstract

Harvesting branches, stumps and unmercantable tops, in addition to stem wood, decreases the carbon input to the soil and consequently reduces the forest carbon stock. We examine the changes in the forest carbon cycle that would compensate for this carbon loss over a rotation period and lead to carbon neutral forest residue bioenergy systems. In addition, we analyse the potential climate impact of these carbon neutral systems. In a boreal forest, the carbon loss was compensated for with a 10% increase in tree growth or a postponing of final felling for 20 years from 90 to 110 years in one forest rotation period. However, these changes in carbon sequestration did not prevent soil carbon loss. To recover soil carbon stock, a 38% increase in tree growth or a 21% decrease in the decomposition rate of the remaining organic matter was needed. All the forest residue bioenergy scenarios studied had a warming impact on climate for at least 62 years. Nevertheless, the increases in the carbon sequestration from forest growth or reduction in the decomposition rate of the remaining organic matter resulted in a 50% smaller warming impact of forest bioenergy use or even a cooling climate impact in the long term. The study shows that carbon neutral forest residue bioenergy systems have warming climate impacts. Minimization of the forest carbon loss improves the climate impact of forest bioenergy.

Keywords: climate impact, forest carbon, forest harvest residues, indirect emissions, logging residues, radiative forcing

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Introduction

Forest biomass has been considered a carbon neutral energy source on the assumption that CO₂ emissions from biomass combustion are offset by the growth of the next tree generation (Stupak *et al.*, 2007; EC, 2009). This assumption has been questioned, first because there is a delay between biomass combustion and tree growth, and second because intensifying forest biomass removal reduces the carbon stock or the carbon sink capacity of forests (Schlamadinger *et al.*, 1995; Walker *et al.*, 2010; Holtmark, 2012; Repo *et al.*, 2011; Zanchi *et al.*, 2011; Haberl *et al.*, 2012; Schulze *et al.*, 2012).

Forest harvest residues, that is, branches, unmercantable tops and stumps, are an important source of bioenergy in northern temperate and boreal forests, and the use of these residues for bioenergy production is expected to grow in the future (Mantau *et al.*, 2010; Díaz-Yáñez *et al.*, 2013). Harvesting these residues decreases the carbon input to dead wood, litter and soil carbon pools, and consequently decreases forest carbon stock (Schlamadinger *et al.*, 1995; Palosuo *et al.*, 2001; Zanchi

et al., 2011). This has been shown in empirical and modelling studies on forest stands (Palosuo *et al.*, 2001; Ågren & Hyvönen, 2003; Hope, 2007; Zanchi *et al.*, 2011; Strömberg *et al.*, 2012a), over forest landscapes (McKechnie *et al.*, 2011; Domke *et al.*, 2012), and on a national level (Kallio *et al.*, 2013; Sievänen *et al.*, 2013). Harvesting and energy use of forest residues immediately releases into the atmosphere the carbon that would otherwise have been stored in the biosphere (Repo *et al.*, 2011). Similar emissions occur when tropical forest is converted into energy crop cultivations (Fargione *et al.* 2008; Searchinger *et al.* 2008, 2009; Melillo *et al.* 2009).

Previous studies show the magnitude and the time-dependency of the emissions of forest residue bioenergy (e.g. McKechnie *et al.*, 2011; Repo *et al.*, 2011; Domke *et al.*, 2012). The decrease in soil carbon stocks is the key determinant of the overall greenhouse gas (GHG) emissions of forest residue bioenergy because the emissions from harvesting, processing and transport are usually low (Forsberg, 2000; Wihersaari, 2005; Eriksson & Gustavsson, 2010; Repo *et al.*, 2012). Forest residue bioenergy may temporarily cause even larger GHG emissions per produced energy unit than the use of fossil fuels when harvesting and energy production are started. The emissions decrease over time when the bioenergy

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production is continued because the residues would gradually decompose and release CO₂ even if left in the forest (Lindholm *et al.*, 2011; McKechnie *et al.*, 2011; Repo *et al.*, 2011).

Forest residue bioenergy has a warming impact on the climate because of the timing of the emissions and the slow removal of CO₂ from the atmosphere (Zetterberg *et al.*, 2004; Holmgren *et al.*, 2007; Kirkinen *et al.*, 2008; Sathre & Gustavsson, 2011; Repo *et al.*, 2012). Therefore, carbon balance calculations that assume that the growing forest offsets the 'upfront' bioenergy emissions result in an overestimation of the true climate change mitigation potential of forest bioenergy (Kendall *et al.*, 2009; Cherubini *et al.*, 2011a; Pingoud *et al.*, 2012). In order to take account of both the time-dependence of the GHG fluxes and the atmospheric residence times of GHGs, the potential climate impact impacts must be assessed with a more comprehensive metric than the carbon balance calculations alone, such as radiative forcing (RF) (Zetterberg *et al.*, 2004; Holmgren *et al.*, 2007; Kirkinen *et al.*, 2008; Sathre & Gustavsson, 2011).

To mitigate climate change efficiently with forest bioenergy, it is crucial to understand both the temporal dynamics of emissions and carbon sequestration, and those of atmospheric concentrations of GHGs. Previous studies have paved way for this understanding but have mainly concentrated on either forest carbon balances (Schlamadinger *et al.*, 1995; Palosuo *et al.*, 2001; Melin *et al.*, 2010), or the RF resulting from timing of the emissions (Zetterberg *et al.*, 2004; Cherubini *et al.*, 2011a; Guest *et al.*, 2012). Consequently, the interactions between forest carbon cycle and the atmosphere, and resulting effect on the climate change mitigation performance of bioenergy are still inadequately understood. In addition, it has not been studied under which conditions bioenergy produced from forest residues would be carbon neutral or would not have a warming impact on climate.

The aim of this article is to analyse which changes in the forest carbon cycle would compensate for the carbon loss resulting from forest residue removal, so that forest residue bioenergy could be justifiably claimed as carbon neutral. We combine forest carbon dynamics with the atmospheric dynamics of CO₂ and analyse the potential climate impacts of carbon neutral forest residue bioenergy systems. The objectives of this study are: (i) to analyse which changes in tree growth, forest rotation time and the decomposition rate of the remaining organic matter are needed to compensate for the carbon loss before the next final felling and discuss the probability of the changes; and (ii) to estimate the climate impact of these changes in terms of the cumulative radiative forcing (CRF) metric. In this study, we apply tested and widely used simulation models that have been described in detail in the scientific literature.

Materials and methods

The carbon balance of a forest stand

To study the effect of forest residue removal on forest carbon balance, we compared forest carbon stock development over a period of time with and without forest residue removal after final felling. We identified three possible ways of increasing carbon sequestration to compensate for the forest carbon loss resulting from residue removal over the following rotation period: (i) an increase in the tree growth; (ii) a lengthening of the rotation period; and (iii) a decrease in the decomposition rate of the litter and humus still remaining in the forest. An increase in tree growth increases tree biomass and augments litter input to the soil from living biomass and forest thinnings, whereas the lengthening of the forest rotation period allows trees to grow larger and produce more litter. Then, we calculated how much carbon sequestration should increase through these changes in carbon inflow or outflow to compensate for the carbon loss over the next forest rotation period. The carbon loss was considered to be compensated for when the average of the total forest carbon (biomass and soil) over a rotation period in bioenergy scenarios equalled the corresponding value in the no-residue-removal scenario.

Biomass carbon stock development was simulated with the forest growth and stand level carbon budget model CO2FIX 3.2 (Maser *et al.*, 2003; Schelhaas *et al.*, 2004) in *Picea abies* stands growing in southern Finland (61.88°N, 23.72°E) and having a 90-year forest rotation period. The CO2FIX model is a book-keeping model that simulates annual forest carbon stocks and fluxes at the hectare scale. To simulate biomass growth the model uses as an input the growth rate of the stem biomass. From the growth rate of the stem volumes, growth rates for foliage, branches and roots were calculated with the help of biomass compartment allocation coefficients (Maser *et al.*, 2003; Schelhaas *et al.*, 2004). The CO2FIX model does not include fine roots. The basic simulation case for *Picea abies* is available on the CO2FIX web pages. In this study, we applied the current annual increment values (CAI) for Norway spruce of Kaipainen *et al.* (2004) to simulate stem wood growth. To estimate yearly foliage litter input we used the turnover rates of Kellomäki *et al.* (1992), and for branch and root litter input the turnover rates of Liski *et al.* (2002). The timing and quantity of forest thinnings were adopted from Kaipainen *et al.* (2004). The forest was thinned at the ages of 40, 60 and 80 years. In thinnings and final fellings branches, foliage and roots were directed to litter. In thinnings 15%, and in final fellings 10%, of stem wood was added to the litter pool, half of this amount as unmerchantable tops and half as stumps.

Litter input and the decomposition of organic matter determine the size of soil carbon stock. To simulate changes in soil carbon stocks, we used the litter production estimates from the CO2FIX model as an input to the dynamic litter and soil carbon model Yasso07 (Tuomi *et al.*, 2009, 2011a) with parameter values by Tuomi *et al.* (2011b). In the Yasso07 model, the decomposition rate of different types of soil carbon inputs depends on the chemical composition of the input types and the climate conditions (Tuomi *et al.*, 2009). The decomposition

rate of woody litter also depends on the diameter of the litter (Tuomi *et al.*, 2011a). In this study, we applied a diameter of 2 cm for branches (Raumonen *et al.*, 2011), 6 cm for roots and 30 cm for stumps (Liski *et al.*, 2013). The diameter of the unmercantable top was 3 cm, which corresponds to half the diameter of pulpwood. The other input variables used in the soil carbon stock simulations are shown in Table 1. Initial soil carbon stocks were calculated by running the Yasso07 model over 10 000 years with a yearly carbon input of a 90-year rotation period.

We studied five scenarios: (i) no residue removal after final felling; (ii) bioenergy, that is, forest residue removal after final felling; (iii) bioenergy with a change in tree growth; (iv) bioenergy with a change in the decomposition rate of organic matter; (v) bioenergy with a longer forest rotation period. In the no-residue-removal scenario stumps, branches and unmercantable tops were left to decompose in the forest after stem wood was harvested. In all bioenergy scenarios all branches, unmercantable tops, stumps and 75% of coarse roots were harvested, in addition to saw logs and pulpwood after final felling. Needles were assumed to be left in the forest to prevent nutrient loss, which conforms to the recommended energy wood harvesting practice in Finland (Äijälä *et al.* 2010). The harvest residues were combusted for energy during the harvesting year. To study the influence of the increased carbon sequestration through increased tree growth, the level of current annual increment was raised after forest residue removal to compensate for the carbon loss. No changes in biomass allocation to different tree parts were assumed. Increased carbon sequestration through a decreased decay rate of remaining organic matter was simulated by decreasing precipitation. The effect of lengthening of the forest rotation period was studied by simulating the carbon budget with 90-, 100-, 110- and 120-year rotation periods. The 90-year rotation period is longer than the one that maximizes sustainable biomass yield. Therefore, increasing rotation length brings the rotation period even further away from the 59-year rotation period, which maximizes sustainable biomass yield in these forest stands.

Changes in radiative forcing in forest landscape

Radiative forcing is defined as the change in the net irradiance at the tropopause following, for example, an increase in an atmospheric GHG concentration (IPCC 2007; Shine 2009). A

positive RF tends to warm the Earth, whereas a negative RF has a cooling effect. The use of RF requires fewer assumptions and involves less uncertainty compared to estimating the actual temperature change due to changes in the GHG concentrations. The RF serves a useful metric of the potential climate impacts because it takes into account the time-dependence of the key processes (e.g. Kendall *et al.*, 2009; Sathre & Gustavsson, 2011). In this study, the climate impacts were expressed in terms of the CRF, which is a time integral of the instantaneous RF. The CRF indicates the change in the energy balance of the Earth system during a certain period of time.

To study the climate impacts of different bioenergy scenarios, we simulated cases in which a forest landscape with no forest residue removal was gradually taken into forest bioenergy production. As a starting point for all scenarios, the forest landscape was composed of equal areas of forest stands of 90 age classes. The forest stands were identical in stocking, density and structural conditions, but differed in age. Each year one age class was harvested, so that the first stand would be ready to be harvested again at the end of the rotation period. In the no-residue-removal scenario, the carbon stocks of the forest landscape remained constant over time with consistent annual harvests. Correspondingly, in the no-residue-removal scenario the annual net CO₂ flux from the forest landscape into the atmosphere was zero, because the growing trees of the forest stands absorb the same amount of CO₂ as released from the decomposition of forest residues of the harvested forest stand. In the bioenergy scenarios, we calculated the yearly net CO₂ flux of the forest landscape into the atmosphere assuming that the forest residues of each year were collected from one stand that had reached the age of final felling and that the residues were combusted for energy at the end of the harvesting year. Depending on the scenario, the forest residue removal was followed by a change in the carbon sequestration. This methodology could not be applied to the scenarios in which the rotation length was changed because there is no unambiguous way to elongate rotation periods on a forest landscape. Therefore, no RF estimates were calculated for these scenarios.

We calculated the globally averaged CRF resulting from the CO₂ flux changes over the forest landscape in different scenarios with the modified version (Lohila *et al.* 2010) of the REFUGE model (Monni *et al.* 2003). In this model, RF is estimated by integrating the response function related to the decay of a series of annual concentration pulses over a period of time, taking into account the annual variation in the emissions,

Table 1 The values of the input variables applied in the soil carbon stock simulations

Chemical composition of litter	Acid hydrolysable compounds	Water soluble compounds	Ethanol soluble compounds	Klason lignin
Branch/stem/ stump/root	68%	1%	1%	30%
Needles	51%	9%	5%	35%
Climate	Mean annual temperature (3.2 °C)	Temperature amplitude (11.6 °C)	Precipitation (681 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, 1991) and Berg & Wessén (1984). 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.

uptake and background concentrations of the most important long-lived GHGs. In this study, we only included CO₂, because the CH₄ and N₂O emissions from collecting, chipping and transporting the forest residues are low compared to emissions from changes in carbon stocks (Palosuo *et al.*, 2001; Wihersaari, 2005; Repo *et al.*, 2012), and furthermore equal in all the bioenergy scenarios studied. We calculated the RF change as a marginal change with respect to a varying background concentration that was assumed to follow the SRES A2 scenario (IPCC 2001).

Results

Forest carbon stocks

Forest residue harvesting decreased the average total forest carbon over the rotation period by 9 t C ha⁻¹ from 159 to 150 t C ha⁻¹ (Table 2). The litter and soil carbon stocks decreased, because collecting branches, stumps and unmercantable tops after final felling decreased the mean carbon input from harvests to soil from 1.04 to 0.71 t C ha⁻¹ yr⁻¹ (Fig. 1). The litter production of living trees was equal in both scenarios (see Fig. 4). The litter input from living biomass and thinnings in the bioenergy scenario did not compensate for the carbon loss resulting from forest residue harvesting before the next final felling (Table 2). The difference in the total carbon stock was 29 t C ha⁻¹ immediately after final felling, and it was reduced to 4 t C ha⁻¹ by the end of the rotation period (Fig. 1).

To compensate for the carbon loss resulting from forest residue harvesting a 10% increase in tree growth or delaying the final felling for 20 years from 90 to 110 years was needed (Figs 1 and 2). These changes lead to an average total forest carbon stock over the rotation period equal to that in the no-residue-removal scenario (Table 2). Both changes augmented the mean litter input over the rotation period from living trees from 1.39 to 1.53 t C ha⁻¹ yr⁻¹. However, these changes

did not prevent soil carbon loss (Table 2). This is because less carbon was directed to the soil than in the no-residue-removal scenario, although the increase in tree growth or the postponement of the final felling increased litter input to the soil by comparison with the bioenergy scenario (Fig. 2) (see Fig. 4).

To recover the soil carbon stock loss, a 38% increase in tree growth or a 21% decrease in the decomposition rate of the remaining organic matter was required (Figs 1 and 3). Delaying final felling for 10, 20 or 30 years did not compensate for the soil carbon loss before the next final felling (Table 2). The 38% increase in tree growth augmented litter input from living trees and harvests, which resulted in a 17% higher mean annual carbon input to the soil than in the no-residue-removal scenario. This larger litter input was needed because the carbon loss resulting from forest residue harvesting occurred instantaneously, whereas the recovery of soil and litter carbon stock occurred gradually over time (Figs 1 and 4).

The total carbon stock was smaller in the bioenergy scenarios than in the no-residue-removal scenario for 22 or 37 years when residue harvesting was followed by a 38% or 10% increase in tree growth. The total carbon stock was smaller for 38 years when the decomposition rate of the remaining organic matter was decreased by 21%. After these time periods, the increased carbon sequestration resulted in higher total carbon stocks than in the no-residue-removal scenario. (Figs 1–3).

Cumulative radiative forcing

All the bioenergy scenarios studied first increased the atmospheric concentration of CO₂, and consequently increased the CRF (Fig. 5). This is because forest residue removal and the subsequent combustion released the carbon of the residues into the atmosphere sooner than natural decomposition in the forest would do, and

Table 2 The average carbon stock of biomass, soil and total carbon over a rotation period when forest residues are left to decompose in the forest or harvested for bioenergy after final felling. In the bioenergy scenarios an increase in current annual increment (CAI), a postponement of final felling or a decrease in the decomposition rate increase carbon sequestration after harvest residue removal

Scenario	Biomass (t C ha ⁻¹)	Soil (t C ha ⁻¹)	Total (t C ha ⁻¹)
No residue removal	63	96	159
Bioenergy	63	87	150
Bioenergy + 10% CAI	69	90	159
Bioenergy + 38% CAI	87	96	183
Bioenergy rotation period 100 years	69	88	157
Bioenergy rotation period 110 years	76	88	164
Bioenergy rotation period 120 years	83	88	172
Bioenergy –21% decomposition rate	63	96	159

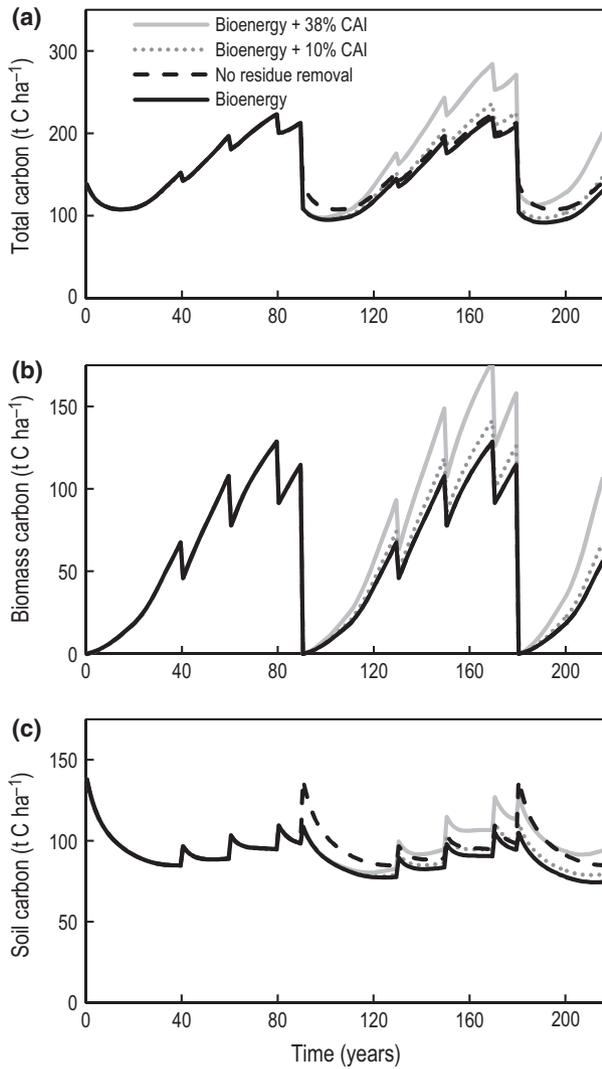


Fig. 1 (a) Total forest carbon, (b) carbon in biomass and (c) soil carbon in a Norway spruce forest in southern Finland when forest residue harvesting is followed by an increase in current annual increment (CAI). Forest residue harvesting is started after the final felling in the year 90.

because the possible increase in carbon sequestration occurred gradually over the next rotation period (Figs 1–3).

In terms of CRF, forest harvest residue removal followed by a 38% increase in forest growth had a warming impact on climate for 62 years, and subsequently a cooling impact. All other bioenergy scenarios had a warming impact during the time period studied (Fig. 5).

Changes in carbon sequestration improved the climate impacts of forest bioenergy. After 20 years the warming impact on climate was reduced, depending on the scenario, by 3–14% compared to the bioenergy scenario. After 90 years, the 10% increase in tree growth and the decrease in decay rate had approximately a

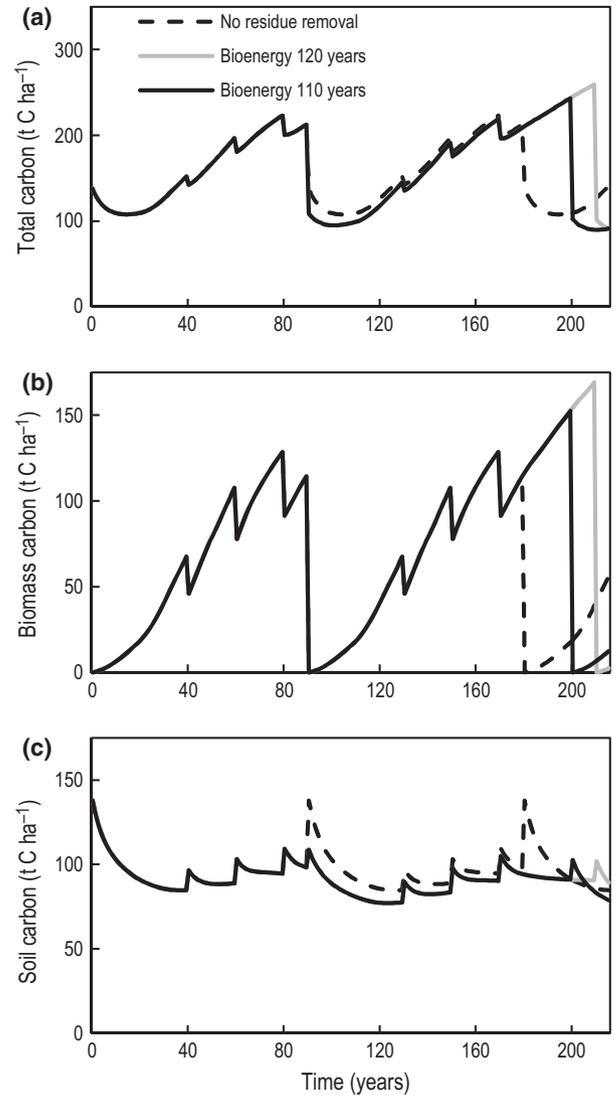


Fig. 2 a) Total forest carbon, b) carbon in biomass, and c) soil carbon in a Norway spruce forest in southern Finland when forest residue harvesting is followed by lengthening of the next rotation period. Forest residue harvesting is started after the final felling in the year 90.

50% smaller warming climate impact compared to the bioenergy scenario.

Discussion

This study shows that even carbon neutral forest residue bioenergy systems may have a warming impact on the climate. Increased carbon sequestration can compensate for the carbon loss resulting from forest residue removal, so that no net CO₂ emissions occur over a forest rotation period. In that case, these systems can be considered carbon neutral. Nevertheless, a warming climate impact occurs because of the time lag between the

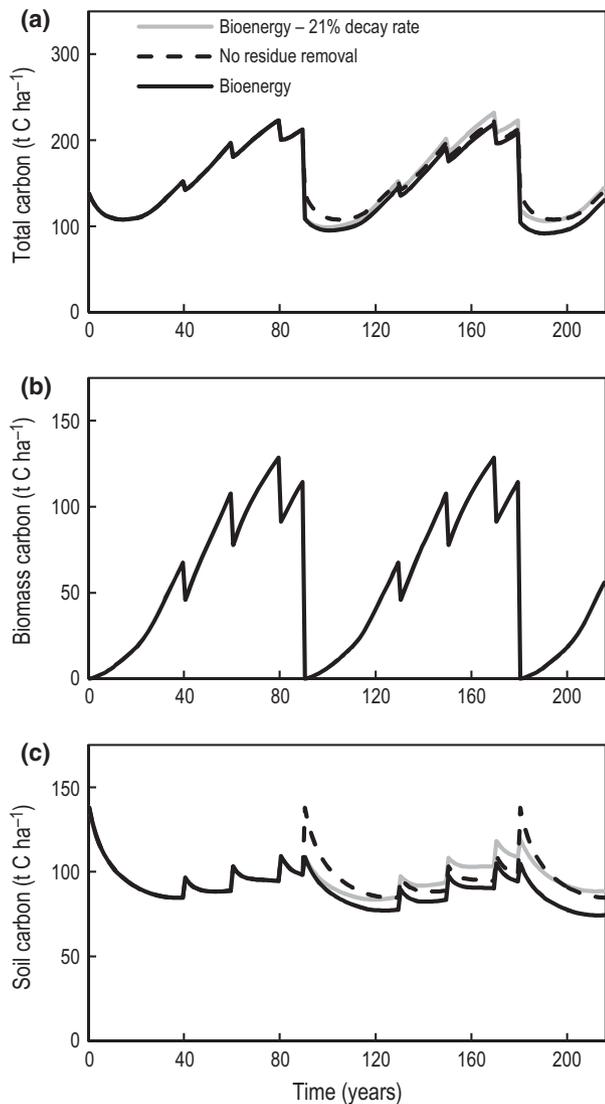


Fig. 3 a) Total forest carbon, b) carbon in biomass, and c) soil carbon in a Norway spruce forest in southern Finland when forest residue harvesting is followed by a decrease in decomposition rate of organic matter. Forest residue harvesting is started after the final felling in year 90.

carbon loss and the increased carbon sequestration: the carbon loss occurs instantaneously, whereas the carbon compensation takes decades. Therefore, as Cherubini *et al.* (2011a,b) state, carbon neutrality over a forest rotation period does not guarantee climate neutrality. Forest residue removal followed by an increase in carbon sequestration can lead to even larger forest carbon stocks at the end of the rotation period than leaving residues to decompose in the forest. However, it may take a very long time until this larger forest carbon stock offsets the warming impact resulting from forest residue removal, because of the temporal dynamics of emissions

and carbon sequestration, and the atmospheric dynamics of CO₂.

An increase in tree growth can balance the carbon loss resulting from forest residue harvesting after final felling, and consequently even cut the warming climate impact of forest bioenergy by 50%. However, field studies have shown that logging residue harvesting often has negative short to medium term effects on forest productivity (Blanco *et al.*, 2005; Fleming *et al.*, 2006; Raulund-Rasmussen *et al.*, 2008; Thiffault *et al.*, 2011). The effects of forest residue removal on site productivity may vary greatly depending on the tree species, the site characteristics and the intensity of soil disturbance (Walmsley & Godbold, 2010; Thiffault *et al.*, 2011; Wall, 2012). There are only a few studies on long-term impacts of forest residue harvesting on tree growth (Walmsley & Godbold, 2010; Thiffault *et al.*, 2011), but it is improbable that forest residue harvesting would increase tree growth to an extent, which would balance the carbon loss resulting from this activity.

If forest residue removal alone does not increase tree growth sufficiently to compensate for the carbon loss, fertilization can be used as a means to boost tree growth and litter input to the soil (Mäkipää, 1995; Jandl *et al.*, 2007). In this study, doubling of the stem volume and a maximum current annual increment of 14 m³ ha⁻¹ yr⁻¹ was needed to prevent soil carbon loss. Such high growth increases have been achieved with intensive fertilization in Nordic studies (Nilsen, 2001; Nohrstedt, 2001). In field studies, nitrogen addition has increased soil carbon stocks (Johnson & Curtis, 2001), which results from an increase in litter input but also from a decrease on decomposition rate (Söderström *et al.*, 1983; Olsson *et al.*, 2005). The long-term effects depend on the site fertility and the added nitrogen compound (Martikainen *et al.*, 1989). According to Sathre & Gustavsson (2012) the additional GHG emissions and consequent climate impacts from fertilizer production and application are small compared to carbon stock benefits. Nevertheless, there are other environmental concerns related to forest fertilization, such as nutrient leaching, increased risk of frost- and fungus-induced damages in trees and changes in the species composition of the flora and the soil fauna (e.g. Saarsalmi & Mälikönen, 2001).

In this study, a reduction equal to one-fifth in the decomposition rate of the remaining organic matter was needed to compensate for the carbon loss. This was achieved with a decrease of 230 mm, or one-third, in annual precipitation. Forest residue harvesting may change the microclimatic conditions of the underlying soil and, and therefore alter microbial activity (e.g. Lattimore *et al.*, 2009). However, it is unlikely that collecting forest residues would significantly decrease decomposition rate in mineral soils. On the contrary, stump

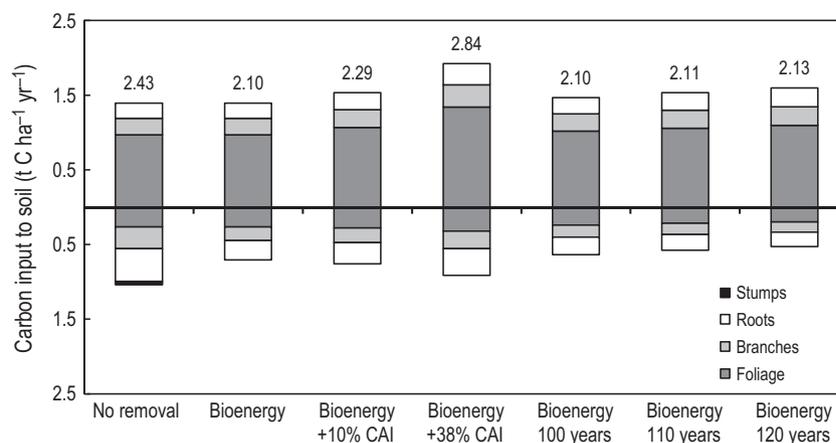


Fig. 4 Mean annual carbon input to the soil from different Norway spruce biomass compartments in bioenergy scenarios. Above the x-axis is litter production from living trees and below harvest residues. The figures on the end of the bars show the total litter input from living biomass (top) and harvests (below). In the figure unmercantable tops are combined with branches.

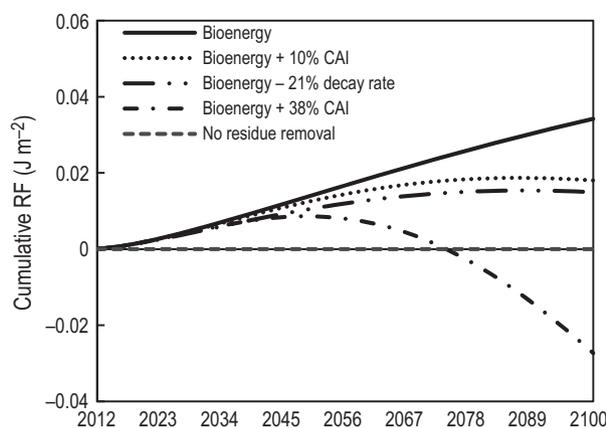


Fig. 5 Cumulative radiative forcing when forest landscape with no forest residue removal is taken into bioenergy production. Forest landscape consists of equal areas of forest in each age class. Each year the oldest stand is harvested and forest residues are collected for bioenergy, and a new stand is established. The radiative forcings are calculated per forest hectare.

harvesting can accelerate decomposition because of disruption of soil (Johansson, 1994; Jandl *et al.*, 2007; SLU, 2009). The long-term effects of stump harvesting are uncertain (Strömgren *et al.*, 2012b). A slower decomposition rate associated with drier climatic conditions may also result from climate change. Nevertheless, in Finland climate change is considered likely to increase the mean annual precipitation as well as the mean temperature (Jylhä *et al.*, 2009). Generally, climate change is likely to increase decay rate (Brovkin *et al.*, 2012). If the decrease in the decay rate of organic matter or the increase in tree growth resulted from climate change then this change would also occur in the scenario in which forest residues are not removed.

The increase in tree growth that brings the average total forest carbon to the same level as in the no-residue-removal scenario did not prevent soil carbon loss. The reductions in soil carbon stocks are noteworthy, because over half of the world's forest carbon is stored in the soil and litter carbon pools, and in boreal forests soils store three times as much carbon as above-ground biomass (Pan *et al.*, 2011). Even small changes in this large stock can have impacts on the global carbon cycle (Peng *et al.*, 2008). Forest carbon pools differ in their dynamics: plant processes may respond quickly to changes while the long-term responses are determined by slow changes in the soil carbon pool (Rastetter *et al.*, 1991; Mäkipää, 1995). Therefore, including litter and soil carbon pools in forest dynamics analysis gives a more comprehensive picture of the climate impact of forest bioenergy.

Allocating forest residue removal to quickly decomposing biomasses can decrease the resulting carbon loss and the warming climate impacts (Repo *et al.*, 2012). This study is based on an intensive forest residue harvesting scenario in which most of the residues are collected and used for bioenergy production. Consequently, the study demonstrates the carbon dynamics of the worst case scenario for harvest residue removal in the climatic conditions considered. Focusing forest residue harvesting on quickly decomposing residues would reduce the level of increased carbon sequestration needed to obtain carbon neutral forest bioenergy, and shorten the time lag between carbon loss and compensation. Nevertheless, intensifying biomass removal from existing forests in the form of forest residue harvesting or additional stem wood harvests reduces forest carbon stocks and sinks (Schlamadinger *et al.*, 1995; Walker *et al.*, 2010; Hudiburg *et al.*, 2011). Therefore, forest

bioenergy will not always result in deep emission reductions needed to mitigate climate change in the next decades (McKechnie *et al.*, 2011; Repo *et al.*, 2012; Schulze *et al.*, 2012).

Previous studies show that changes in forest management may reduce the warming impact of forest bioenergy on the climate (Cherubini *et al.*, 2011b; Routa *et al.*, 2012; Sathre & Gustavsson, 2012). Modelling studies indicate that an increase in forest density compared to current recommendations or intensive fertilization decrease life cycle CO₂ emissions (Alam *et al.*, 2012; Routa *et al.*, 2012) and improve the climate impact (Sathre & Gustavsson, 2012). An increase in the growth rate, an elongation of rotation period or a combination of these reduce the warming impact on the climate in terms of RF (Cherubini *et al.*, 2011b). However, these results cannot be quantitatively compared to the findings of this study because the earlier studies include the material and energy substitution effect in the RF change, exclude changes in soil carbon stock, assume that all above-ground biomass is harvested for energy production or consider only one forest stand (Cherubini *et al.*, 2011b; Guest *et al.* (2012); Sathre & Gustavsson, 2012). The carbon balance calculations show only emissions per energy unit over a forest rotation period, and do not account for the dynamics of the atmospheric concentrations of the GHGs (Alam *et al.*, 2012; Routa *et al.*, 2012).

This study and previous studies on forest residue bioenergy indicate that current forest management and forest residue harvesting practices do not guarantee either carbon neutral or climate neutral forest bioenergy (e.g. Kirkinen *et al.*, 2008; McKechnie *et al.*, 2011; Zanchi *et al.*, 2011; Domke *et al.*, 2012). However, our study demonstrates that changes in the forest carbon cycle can significantly improve the climate impacts of forest bioenergy. A comprehensive view on temporal dynamics of carbon emissions and sequestration and consequent climate impacts of forest bioenergy systems are important when planning forest management to maximize climate benefits achieved with forest residue bioenergy.

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