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Sustainability of forest bioenergy in Europe: land-use-related carbon dioxide emissions of forest harvest residues

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Abstract

Increasing bioenergy production from forest harvest residues decreases litter input to the soil and can thus reduce the carbon stock and sink of forests. This effect may negate greenhouse gas savings obtained by using bioenergy. We used a spatially explicit modelling framework to assess the reduction in the forest litter and soil carbon stocks across Europe, assuming that a sustainable potential of bioenergy from forest harvest residues is taken into use. The forest harvest residue removal reduced the carbon stocks of litter and soil on average by 3% over the period from 2016 to 2100. The reduction was small compared to the size of the carbon stocks but significant in comparison to the amount of energy produced from the residues. As a result of these land-use-related emissions, bioenergy production from forest harvest residues would need to be continued for 60–80 years to achieve a 60% carbon dioxide (CO_2) emission reduction in heat and power generation compared to the fossil fuels it replaces in most European countries. The emission reductions achieved and their timings varied among countries because of differences in the litter and soil carbon loss. Our results show that extending the current sustainability requirements for bioliquids and biofuels to solid bioenergy does not guarantee efficient reductions in greenhouse gas emissions in the short-term. In the longer-term, bioenergy from forest harvest residues may pave the way to low-emission energy systems.

Keywords: carbon debt, indirect emissions, logging residues, RED, soil carbon, sustainability criteria

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Introduction

Bioenergy plays a crucial role in plans to achieve climate and energy policy targets agreed in the European Union (COM, 2010; Beurskens & Hekkenberg, 2011; Szabó *et al.*, 2011). The annual demand for bioenergy is estimated to increase from the present 5.7 to 10 EJ by 2020 (Bentsen & Felby, 2012). According to the National Renewable Energy Action Plans (NREAPs) of the EU countries, the use of biomass for heating and cooling will double between 2005 and 2020 to account for 80% of the total in the EU-26 countries. Correspondingly, the use of biomass in electricity generation will triple during the same time period to represent 19% of the total renewable electricity.

One option to fulfil the growing need for bioenergy is to increase the use of forest harvest residues for energy production. The residues are comprised of branches, nonmerchantable tops, stumps and other residual biomass from forestry operations that are traditionally left in the forest after timber harvesting (UNECE, 2008; Mantau *et al.*, 2010; Díaz-Yáñez *et al.*, 2013).

Estimates of energy potential in forest harvest residues range from 0.4 to 2.3 EJ yr^{-1}, and additional fellings may expand this range from 0.8 to 10.6 EJ yr^{-1} in Europe (EEA, 2006, 2007; Ericsson & Nilsson, 2006; Alakangas *et al.*, 2007; Asikainen *et al.*, 2008; UNECE, 2008; Anttila *et al.*, 2009; Haberl *et al.*, 2010; de Wit & Faaij, 2010; Bentsen & Felby, 2012). The range of the estimates is wide depending on whether the studies approximated theoretical, technological or economic potentials and which constraints they applied (Rettenmaier *et al.*, 2010; Offermann *et al.*, 2011; Bentsen & Felby, 2012). Other reasons for the wide range are differences in applied conversion factors, in definitions of biomass fractions, and in temporal and geographical scopes (Bentsen & Felby, 2012). In addition, some studies used demand-driven approaches, whereas others applied resource-focused ones (Offermann *et al.*, 2011).

Intensification of biomass removals from forests has raised concerns about the environmental effects on

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forest productivity, biodiversity, soil quality, and climate change mitigation potential of forest bioenergy (Lattimore *et al.*, 2009; Walmsley & Godbold, 2010; Thiffault *et al.*, 2011; Agostini *et al.*, 2013; Fritsche & de Jong, 2013). The estimates for the sustainable potential of forest bioenergy have taken into account some of the possible effects (e.g., EEA, 2006, 2007; UNECE, 2008). However, the environmental constraints considered have mainly been related to site productivity, biodiversity, erosion, water regulation, and soil properties (EEA, 2006, 2007; Böttcher *et al.*, 2010; Verkerk *et al.*, 2010, 2011). In some cases, the sustainable levels of forest harvests are seen to guarantee the sustainability of forest bioenergy (de Wit & Faaij, 2010).

The European Renewable Energy Directive (RED) defines sustainability criteria for biofuels and bioliquids (2009/28/EC). The RED mandates that greenhouse gas (GHG) emission savings from the use of biofuel over the life-cycle shall be at least 60% compared to the use of fossil fuels from 2018 onwards. In addition, the raw material shall not be obtained from land with high biodiversity value or high carbon stock (2009/28/EC). Although the RED does not mandate sustainability criteria for solid biomass, there is an ongoing discussion on defining sustainability requirements also for solid and gaseous biomass used in electricity generation, heating and cooling (COM, 2010; Fritsche & de Jong, 2013). It is currently foreseen that the criteria will be linked to the existing criteria for biofuels and bioliquids (COM, 2010; Lamers *et al.*, 2013). The government of the United Kingdom has already introduced national sustainability criteria for the solid biomass used for electricity generation (OFGEM, 2011).

One motivation for defining the sustainability criteria for biofuels in the EU is the effort to avoid bioenergy-related emissions from direct and indirect land-use changes (EC, 2009; COM, 2013). This is because converting forests to energy crop cultivations or land clearing for delocalised food production often reduce carbon stocks of biomass, soil, or both (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009; Melillo *et al.*, 2009). The reductions in the carbon stocks may offset some or all of the emission savings of bioenergy (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009).

The emissions resulting from the reductions in the carbon stocks are not limited to land-use change but can occur within the same land use, as a consequence of altered management, for example, when harvesting of forest biomass is intensified (Melin *et al.*, 2010; Lindholm *et al.*, 2011; McKechnie *et al.*, 2011; Repo *et al.*, 2011; Zanchi *et al.*, 2011; Domke *et al.*, 2012). Increasing forest residue harvesting reduces litter input to the soil, and consequently reduces the carbon stock and sink of the soil (e.g., Schlamadinger *et al.*, 1995; Palosuo *et al.*, 2001; Hope, 2007; Sievänen *et al.*, 2014). Even small changes in the soil carbon stocks may have significant effects on the climate (Peng *et al.*, 2008), because soil contains two to three times as much carbon as the atmosphere or the terrestrial vegetation globally (Peng *et al.*, 2008; Pan *et al.*, 2011). Despite of this probable importance, previous studies estimating the sustainable forest harvest residue potentials have not considered the effects of intensified biomass harvesting on the European litter and soil carbon stocks or analysed the amount of GHG emissions that can be avoided by exploitation of the otherwise environmentally compatible forest bioenergy potential (EEA, 2006).

The objectives of this study were to (i) investigate the change in the European litter and soil carbon stocks assuming that a sustainable bioenergy potential of forest harvest residues is taken into use; and (ii) estimate the CO_2 emission reductions achievable with forest harvest residue bioenergy in different EU countries. We used a spatially explicit modelling framework to investigate the reduction in the carbon stocks, and contrasted these simulated reductions with the amounts of energy produced from the forest biomass to estimate the land-use-related CO_2 emissions of forest harvest residue bioenergy across Europe.

Materials and methods

Approach

We developed a framework that links spatially explicit information on forest biomass and harvests to litter and soil carbon stocks in Europe. The framework consisted of two models: the Global Forest Model G4M (Kindermann *et al.*, 2013) estimating the development of standing stem volume under changing forest management and environmental conditions, and the Yasso07 soil carbon model simulating the corresponding changes in litter and soil carbon stocks (Tuomi *et al.*, 2008, 2009, 2011a,b). We conducted the calculations by 25 × 25 km grid cells across our study area.

Biomass carbon stocks

The development of the European forests over the 21st century was simulated with the G4M model (Tietjen *et al.*, 2010). We assumed harvesting according to the current practices and the climate change following the IPCC SRES A1B emission scenario (Tietjen *et al.*, 2010). In our simulations, we used the medians of the different model outputs (Mitchell & Philip, 2005; Tietjen *et al.*, 2010).

The initial growing stock of stem wood in each grid cell was based on a forest biomass map (Kindermann *et al.*, 2008). Forest growth was estimated according to a map of the potential Net Primary Productivity (NPP) (Cramer *et al.*, 1999). The climate change affected the NPP estimates over our simulation period (Tietjen *et al.*, 2010), and consequently our simulated estimates of forest growth. The estimates of initial stem wood stock and the NPP-based yield level estimates determined the forest rotation length in each grid cell (Kindermann *et al*., 2008). We assumed an even distribution of age classes and a fixed harvesting age over the time period studied in each grid cell.

The G4M estimates of the stock and harvests of stem wood were converted to total tree biomass and litter input to the soil according to a calculation scheme shown in Fig. 1. The biomasses of branches, foliage, roots, and stumps were estimated from stem biomass with biomass equations that used diameter at breast height (DBH) and tree height as explanatory variables (Table 1, DBH and height calculation described in Kindermann *et al*., 2013). We applied these equations to determine the ratios of foliage/stem, branch/stem, stump/stem, and roots/stem, and thus the estimates of the stocks of foliage, branch, stump, and root biomass in each grid cell. The annual litter flow to the soil consisted of litter from standing biomass, harvest residues and harvest losses (Fig. 1). The litter input to the soil from living trees was estimated by applying tree-compartment-specific turnover rates separately for coniferous and broadleaved species groups (Liski *et al*., 2002). The carbon input to the soil from the harvest losses was calculated as the difference between stocking stem wood and harvested logs.

Litter and soil carbon stock

The changes in the litter and soil carbon stocks were simulated using the dynamic soil carbon model Yasso07. This model has been shown to give unbiased estimates for the decomposition of nonwoody and woody litter (Tuomi *et al*., 2009, 2011a). The validity of the Yasso07 model has been tested on global (Tuomi *et al*., 2009; Thum *et al*., 2011), national (Rantakari *et al*., 2012; Ortiz *et al*., 2013), and site scales (Karhu *et al*., 2011; Lu *et al*., 2013). Based on these studies, the Yasso07 is suitable for estimating the decomposition rate of litter, the carbon stocks of litter and soil, and the changes in these stocks in this study.

The Yasso07 model describes the litter decomposition and the soil carbon cycle based on the chemical quality of the organic matter and climatic conditions (Tuomi *et al*., 2009). The decomposition of woody litter depends also on the physical size of the litter (Tuomi *et al*., 2011a). The model is based on more than 15 000 measurements of litter decomposition and soil organic carbon stocks across the globe, and the parameter values are determined from these measurements using Bayesian inference (Tuomi *et al*., 2009, 2011a). To avoid overparameterization, the Bayesian model comparison has been used in the development of the model (Tuomi *et al*., 2009, 2011a).

The Yasso07 model divides nonwoody and woody litter into four chemically distinguishable fractions that decompose at their unique rates. The fractions are (i) water soluble (W); (ii) ethanol soluble (E); (iii) acid hydrolysable (A); and (iv) neither soluble nor hydrolysable (N). In addition, there is a humus (H) fraction consisting of more recalcitrant compounds formed of the decomposition products of the A, W, E, and N fractions. We derived the chemical composition of the litter for the simulations from various earlier studies (Table 1). Diameters applied in the simulations were 2 cm for branches and roots, 7 cm for harvest losses and 35 cm for stumps.

The initial litter and soil carbon stocks for each cell were estimated by running the Yasso07 model for 10 000 years to a steady-state with a constant average litter input of the years 2011 to 2015 and a constant average climate of a period from

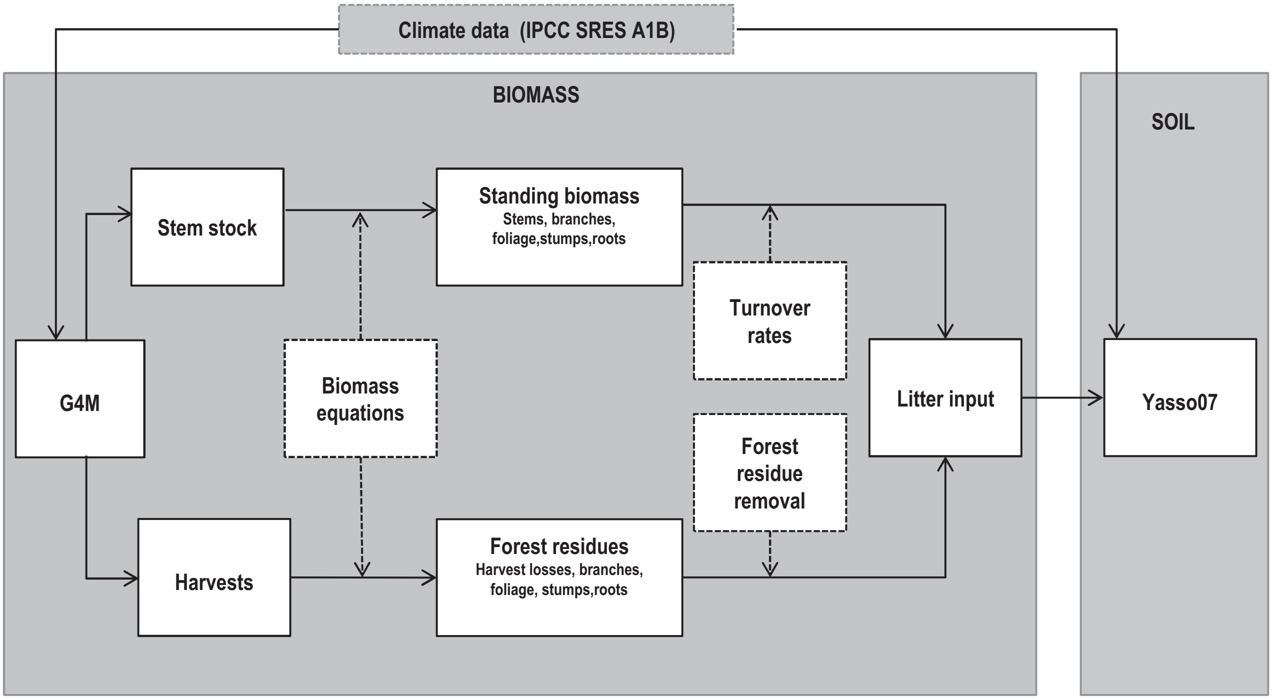

Fig. 1 Calculation scheme to estimate the effects of forest harvest residue removals on the carbon stocks of litter and soil across Europe.

Table 1 Biomass equations applied to estimate tree biomass and the chemical composition of litter used in the decomposition simulations in terms of the shares of acid hydrolysable compounds (A), water soluble compounds (W), ethanol soluble compounds (E) and compounds neither soluble nor hydrolysable (N)

Species group	Biomass equations	Tree part	A	W	E	N
Temperate broadleaved evergreen	aboveground biomass dbh < 30 cm [1] dbh > 30 cm [2] stump-root biomass[3]	Stem, branch, roots, stump[6]	0.76	0.01	0.01	0.22
		Foliage, fine roots[7,8]	0.49	0.15	0.08	0.29
Temperate broadleaved summergreen	aboveground biomass dbh < 30 cm [1] dbh > 30 cm [2] stump-root biomass[4]	stem, branch, roots, stump[9]	0.76	0.01	0.01	0.22
		foliage, fine roots[9-12]	0.39	0.09	0.05	0.47
Boreal broadleaved summergreen	above- and belowground biomass[4]	stem, branch, roots, stump[9]	0.76	0.01	0.01	0.22
		foliage, fine roots[9-12]	0.39	0.09	0.05	0.47
Temperate coniferous	above- and belowground biomass[5]	stem, branch, roots, stump[9]	0.68	0.02	0.01	0.29
		foliage, fine roots[9-12]	0.51	0.13	0.10	0.26
Boreal coniferous	above- and belowground biomass[5]	stem, branch, roots, stump[9]	0.68	0.01	0.05	0.26
		foliage, fine roots[9-12]	0.50	0.09	0.05	0.36

References: 1) Bartelink (1997), 2) Cienciala *et al.* (2005), 3) Goff & Ottorini (2001), 4) Repola (2009), 5) Repola (2008), 6) Pettersen (1984), 7) Gholz *et al.* (2000), 8) Trofymow (1995), 9) Hakkila (1989), 10) Berg *et al.* (1984), 11) Berg and Wessén (1984), 12) Berg *et al.* (1991).

1980 to 2010. The time period of the litter input values used was rather short to account for temporal variability in litter input caused by varying harvesting levels. In our approach, this problem was compensated by the fact that each grid cell contained forests of different age classes and tree species groups.

We evaluated the reliability of our approach by comparing the results to independent estimates of biomass, litter production and soil carbon stocks (see Data S1). Our estimates of aboveground tree biomass, total litter input, and soil carbon stocks were comparable to data compiled by FAO (2010) and earlier estimates calculated using the European Forest Information Scenario Model EFISCEN (Sallnäs, 1990; Schelhaas *et al.*, 2007). These comparisons supported the adequacy of our approach for the present study.

Sustainable forest bioenergy potential

To estimate an annual sustainable bioenergy potential from forest harvest residues, first, we calculated the total quantity of the residues in each European country in the year 2011 using the G4M model. Second, we calculated the share of the total forest harvest residues that equalled the sustainable potential as proposed by Elbersen *et al.* (2011). This potential has been calculated for the EU-27 countries using methods described in detail by Verkerk *et al.* (2010, 2011). It follows a scenario assuming that regulations and practices enabling or restricting forest operations will be similar to those today, and takes into account several environmental, technical and social constraints, including requirements of workforce, forests not available for wood supply, site productivity and soil erosion risk (Verkerk *et al.*, 2010, 2011).

The sustainable share of forest harvest residues ranged from 2% to 44% depending on the country. In our simulations the proportions of branches, harvest losses and stumps were equal and did not change over time. For the non-EU-27 countries, we assumed that 15% of forest residues were harvested, which corresponds the median value among the EU-27 countries. The 15% share was applied also for Ireland and the United Kingdom because the G4M estimate of the total forest harvest residue potential was lower than the constrained potential proposed by Elbersen *et al.* (2011). Cyprus and Malta were excluded from the analysis because of lack of information.

In the forest carbon simulations the sustainable share of the forest harvest residues was allocated to bioenergy production from each grid cell and year starting from the year of 2016. The sustainable share was constant, whereas the total quantity varied annually according to the harvest level. To estimate the effect of forest harvest residue removal on litter and soil carbon stocks, we simulated the development of the forest carbon stocks with and without forest residue harvesting between 2016 and 2100 and contrasted the results with each other.

Emission reductions with bioenergy from forest harvest residues

We estimated the CO_2 emission savings achievable by using bioenergy from forest harvest residues taking into account the reductions in the carbon stocks of litter and soil. We calculated the average litter and soil carbon loss resulting from the removal and energy use of forest harvest residues in each country and year by summing up the amount of carbon remaining in the decomposing forest harvest residues if they were left in the forests. This cumulative carbon loss was divided by the cumulative energy obtained from the collected forest harvest residues each year to calculate emissions per energy unit (Repo *et al.*, 2011, 2012). Following the European Commission requirements for the sustainability for solid and gaseous fuels in electricity, heating and cooling (COM, 2010) we applied a fossil fuel comparator equal to 198 g CO_2eq MJ^{-1} for electricity generation and a comparator equal to 87 g CO_2eq MJ^{-1} for heating and cooling. To include energy conversion losses we assumed a 25% electrical and a 85% thermal conversion efficiency (COM, 2010). The carbon content of the biomass was assumed to be equal to 44% of dry wood (m/m), wood density 400 kg fresh ton^{-1}, and the energy content 19 MJ kg^{-1}(dry) (Nurmi, 1997; Alakangas, 2000).

Results

Harvesting the sustainable amount of forest residues decreased the simulated carbon stocks of litter and soil on average by 3 t C ha^{-1} by the end of this century in the European forests (Fig. 2). The largest carbon losses per a hectare of forest land occurred in Germany, the United Kingdom, Czech Republic, and Denmark (Fig. 3). On the other hand, the largest losses per country were found in Sweden, Finland, and Germany (Table 2). On average the harvesting of the forest residues decreased the carbon stocks of litter and soil by 3% between 2011 and 2100 in Europe. The relative carbon loss was the highest in the United Kingdom (9.7%) and the lowest Lithuania (0.3%) (Table 2).

The carbon loss was mainly dependent on the amount of forest residues harvested, the availability of forest land for the residue harvesting, and the climatic conditions. The large potential of available forest harvest residues explained the considerable carbon loss in Germany, Finland, and Sweden. The sustainable bioenergy potentials from forest harvest residues differed only little between Germany and Finland, but the carbon loss per a hectare of forest land was larger in Germany because the residues were harvested from a smaller forest area. The high intensity of forest residue harvesting from a small forest area resulted in considerable carbon loss also in the United Kingdom, Denmark, and the Netherlands. The differences in the carbon loss due to climatic conditions were visible within some countries. For example, in the cooler climate conditions of northern Finland, the decomposition of stumps and branches was slower than in southern Finland, and consequently forest residue harvesting reduced the carbon stocks more in the northern than in the southern Finland (Fig. 2).

Because of these variations in the carbon loss, the CO_2 emissions of forest harvest residue bioenergy per produced energy unit differed among the European countries. Consequently, the CO_2 emission savings from fossil fuel substitution varied (Figs 4 and 5). Electricity generation from forest harvest residues caused even larger CO_2 emissions than electricity generation from the reference fossil fuel for the first 5 years in many countries, and in some countries for the first 20 years (Fig. 4). On the other hand, heat production reduced emissions already within a few years in most European countries. The emissions of forest harvest residue bioenergy decreased over time because the rate of carbon loss reduced, as the residues would decompose even if left to decay in forest (Fig. 3). Nevertheless, the 60% reduction in the CO_2 emissions, compared to fossil fuels, required by the current EU RED directive after 2018 was achieved with a continuous forest bioenergy use for heat production in most European countries only after 60 years. Correspondingly, it took more than 80 years to reach to the 60% target in electricity generation (Fig. 5). The emissions decreased slower in Northern European countries than in Southern European countries as a result of lower decomposition rate of the forest harvest residues.

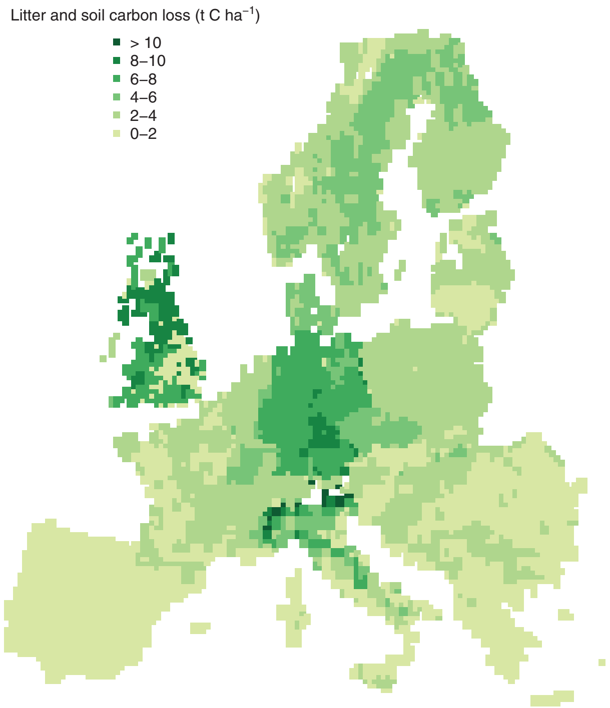

Fig. 2 Loss of litter and soil carbon between 2016 and 2100 resulting from sustainable removals of forest harvest residues.

Heat and power generation from forest harvest residues caused the highest emissions per energy unit in the Netherlands, Ireland, Finland, and Sweden (Figs 4 and 5). In the Netherlands and Ireland, the high emissions resulted from the small forest area available for forest residue harvesting, whereas the combination of a cool climate and a large amount of available felling residues explained the high emissions in the Northern European countries. The emissions per energy unit produced were the lowest in Portugal and Slovenia.

Discussion

An intensification of forest residue harvests and energy use reduced the simulated carbon stocks of litter and

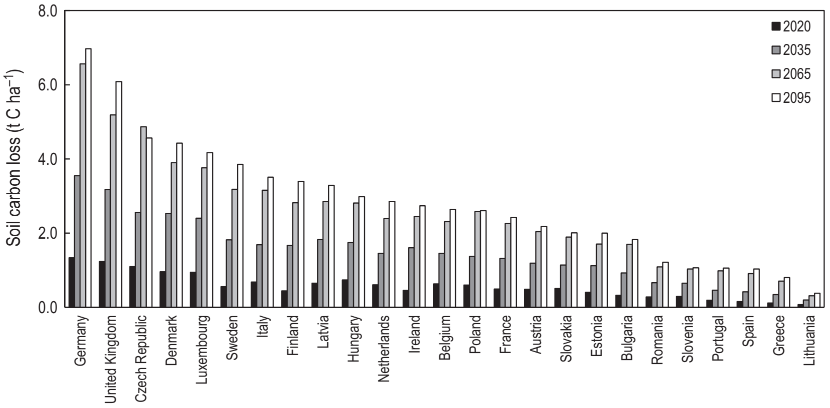

Fig. 3 Development of the average litter and soil carbon loss on forest land resulting from sustainable removals of forest harvest residues since 2016 in the selected EU countries.

Table 2 Loss of litter and soil carbon from between 2016 and 2100 resulting from sustainable removals of forest harvest residues in the studied countries

	Carbon loss (Mt C)	Share of soil carbon stock
Austria	12.6	1.3%
Belgium	1.8	2.6%
Bulgaria	8.2	2.5%
Czech Republic	14.6	2.6%
Denmark	1.3	3.7%
Estonia	3.6	1.1%
Finland	84.4	2.1%
France	37.4	3.6%
Germany	75.3	5.0%
Greece	2.5	3.4%
Hungary	4.8	2.7%
Ireland	<0.1	3.6%
Italy	45.0	8.1%
Latvia	8.2	2.0%
Lithuania	0.6	0.3%
Luxembourg	0.4	3.4%
Netherlands	0.7	2.9%
Poland	21.7	1.6%
Portugal	5.3	3.5%
Romania	13.0	1.1%
Slovakia	5.6	1.3%
Slovenia	1.6	0.9%
Spain	20.1	3.3%
Sweden	130.0	2.4%
United Kingdom	5.7	9.7%

soil across Europe. This reduction was small compared to the size of these carbon stocks but significant when related to the amount of energy produced. As a result of the forest carbon loss, replacement of fossil fuels with forest bioenergy did not result in immediate emission reductions, as has also been shown in previous studies (Walker *et al.*, 2010; McKechnie *et al.*, 2011; Repo *et al.*, 2011; Zanchi *et al.*, 2011; Schulze *et al.*, 2012). According to our study it would take 60 to 80 years to achieve the 60% emission reduction with forest harvest residue bioenergy in heat and power generation in most European countries. This result supports the finding of earlier studies applying the current RED calculation guidelines for liquid biofuels, the minimum GHG emission reduction target of 60% is difficult to achieve if the changes in the carbon stocks of litter and soil are accounted for (Holma *et al.*, 2013; Koponen *et al.*, 2013).

The achievable emission reductions with forest harvest residue bioenergy, and their timings, differed among the European countries. For example, the production of one unit of heat or electricity from forest harvest residues caused 7% higher CO_2 emissions in Finland and Sweden than it did in Slovenia in the year of 2020. In the year of 2095, the corresponding emissions per energy unit were significantly lower in each country because the forest harvest residues would also release CO_2 if left to decompose in forest (Repo *et al.*, 2011). Nevertheless, in the year of 2095, the production of one unit of energy caused as much as 79% higher emissions in the Nordic countries compared to Slovenia. The Nordic countries have the largest potentials of forest bioenergy but the carbon loss, and the consequent land-use-related emissions are also the largest in Europe. The differences between countries may pose a burden sharing issue, how to define mandatory emission reduction criteria given the discrepancy between countries?

Comparisons of our estimates to independent data supported the adequacy of our approach for this study. We assessed the reliability of our results by comparing the estimates of our different calculation steps to independent data because similar studies have not been conducted at a national scale earlier. The country-level estimates of the aboveground biomass in the year of 2011

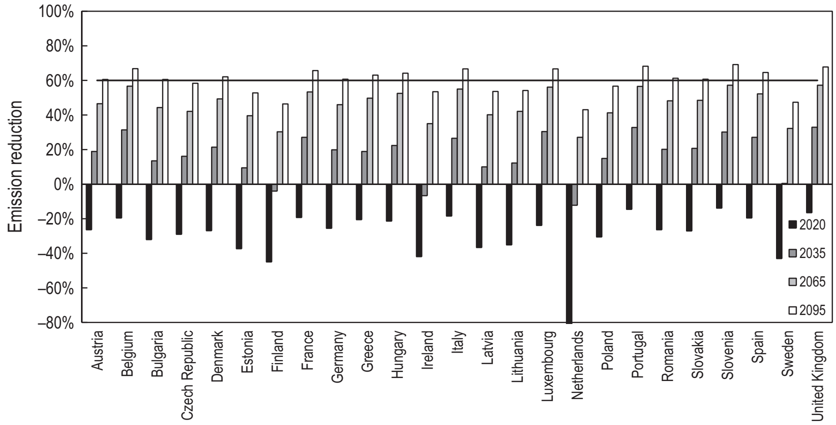

Fig. 4 Development of CO_2 emission reductions when producing electricity from sustainable removals of forest harvest residues since 2016 compared to a reference fossil fuel (EC, 2010). The horizontal line indicates the 60% emission saving limit of the EU RED.

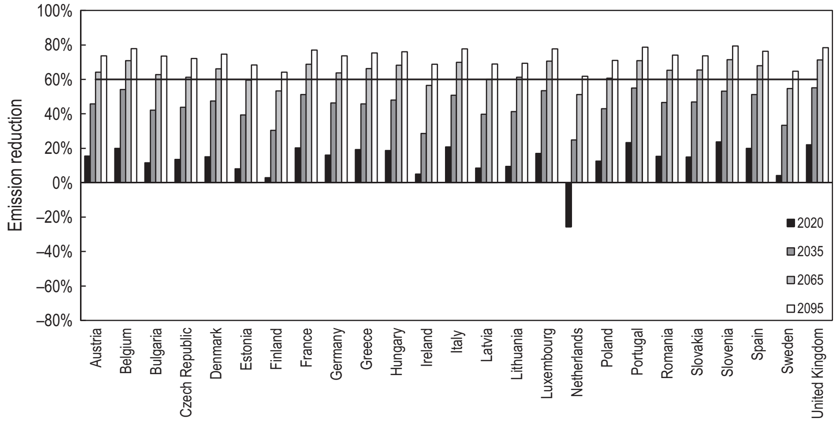

Fig. 5 Development of CO_2 emission reductions when producing heat from sustainable removals of forest harvest residues since 2016 compared to a reference fossil fuel (EC, 2010). The horizontal line indicates the 60% emission saving limit of the EU RED.

were consistent with the FAO (2010) data. Generally, the largest sources of uncertainty in the simulated changes of soil carbon stocks are litter input estimates (Ortiz *et al.*, 2013). Especially, the litter production of fine roots and branches is poorly known (Peltoniemi *et al.*, 2006; Monni *et al.*, 2007). In this study, the total litter input estimates were comparable to those of the EFISCEN model (see Data S1). However, our estimate consisted of more coarse woody litter and less foliage compared to the EFISCEN. These differences in the size distribution may explain our larger initial soil carbon stock estimates, especially in Northern and Eastern Europe. Since the diameter affects the decomposition of woody litter in the model we used (Tuomi *et al.*, 2011a), a better knowledge of the diameter distribution of litter input would decrease the uncertainty of our results. Nevertheless, the general conclusions of our study are not sensitive to these uncertainties. The estimates of forest harvest residue energy potentials in the EU-27 countries differ between studies because of differences in the applied methodologies and constraints (Bentsen & Felby, 2012). The country-specific potentials of this study were of the same order of magnitude compared to previous estimates (Asikainen *et al.*, 2008; Böttcher *et al.*, 2010; Elbersen *et al.*, 2011). These comparisons indicate that our results may be uncertain for individual countries but they support the validity of our results for Europe in general. The possible effects of CO_2 fertilization, species composition changes or changes in forest management were excluded from the analysis.

The emission savings estimated in this study depend on the fossil fuel comparators and the energy conversion efficiencies. The emissions from electricity generation using different fossil fuels vary between 160 and 380 g CO_2eq MJ^{-1} and those from heating between 66 and 127 CO_2eq MJ^{-1} if the conversion efficiency for electricity is 25–35% and that for heating and cooling 75–85% (IPCC, 2006a). Natural gas results in the lowest emissions and coal the highest. The fossil fuels comparators used in this study were in lower end of the ranges.

However, these comparators represent the fossil fuel mixes for electricity generation and heating and cooling in the EU-27 countries (COM, 2010). Thus, they may offer a basis for more realistic estimation of emission savings than either end of the ranges. The largest emissions savings are achieved with forest residue bioenergy by replacing carbon intensive fossil fuels and by deploying energy conversion technologies of high efficiency.

There are concerns that forest residue harvesting may increase the decomposition of organic matter in soil and reduce forest productivity. Soil disturbance, caused by stump harvesting, has been observed to increase CO_2 efflux from the soil (Johansson, 1994; Lundmark-Thelin & Johansson, 1997; Jandl *et al.*, 2007; Walmsley & Godbold, 2010). However, studies on the magnitude, duration and significance of this effect compared to traditional site preparation methods are scarce (SLU, 2009; Strömgren & Mjöfors, 2012; Strömgren *et al.*, 2012), and the long-term impacts are still poorly known (Strömgren *et al.*, 2012). Forest residue harvesting has often negative short and medium-term effects on forest productivity because of increased nutrient removal (Thiffault *et al.*, 2011; Wall, 2012). Accounting for the possible effects of the soil disruption and the decreased forest productivity would reduce the emission savings achieved with forest harvest residue bioenergy compared to the estimates given in this study.

Over the next decades climate change is likely to affect biomass growth, litter production and litter decomposition. The G4M and the Yasso07 are both models driven by climate variables, and can thus account for the effect of the projected changes in climate. The chosen SRES A1B scenario describes a more integrated world with a balanced emphasis on all energy sources. We chose this scenario as one of many likely scenarios to account for the fact that the climate is not going to be stable over the period of 100 years. We found that there was a clear gradient in the total carbon losses that could be partially attributed to climate. In our study, the potential carbon losses resulting from forest residue harvesting tended to be higher in Northern Europe compared to Southern Europe because of the slower decomposition rates in the northern forest ecosystems. In general, the IPCC projections suggest a more intensive warming in higher latitudes (IPCC, 2013). Therefore, the future climate change may affect the emissions from the energy use of forest harvest residues more in northern countries compared to other regions of Europe. An acceleration of decomposition (Brovkin *et al.*, 2012) in the northern forests would lead to higher reference emissions of the forest harvest residues left in the forest, and could therefore reduce the emissions of this bioenergy option compared to the current climate. A more detailed analysis, which is, however, beyond the scope of this paper, should address uncertainties of these emissions associated with climate change. Such analysis would help to better identify regions of high risk of net emissions from an intensified employment of forest harvest residue bioenergy, and regions where biomass extraction could be prioritized.

The timing of the emissions is important for the mitigation of climate change. Substantial reductions in GHG emission are required already in the near future to limit the global warming to less than 2 °C above the pre-industrial temperatures (IPCC, 2007). In previous bioenergy studies, the emissions and the carbon sequestration of ecosystems have been followed over time or they have been assumed to take place at the same time (Lamers & Junginger, 2013). Traditional life-cycle assessments (LCA) of bioenergy do not account for the timing of the emissions (Helin *et al.*, 2012), but recent studies have proposed methods for inclusion of the temporal information (e.g., Levasseur *et al.*, 2010). In the RED sustainability criteria, emissions from land-use change are annualized by dividing the total emissions equally over a 20 year period (2009/28/EC). The same approach is used in many voluntary initiatives for the sustainability certification of bioenergy (Scarlat & Dallemand, 2011). Approaches based on dynamic modelling, like the one we used, make it possible to follow the actual emissions and carbon sequestration from year to year.

The sustainability criteria are set to ensure that increasing bioenergy utilization will deliver significant reductions in GHG emissions, and that it does not lead to biodiversity loss (2009/28/EC). Increasing forest biomass harvests in order to meet the national targets under the EU renewables directive decreases forest carbon sink at the national levels (Kallio *et al.*, 2013; Sievänen *et al.*, 2014), at the EU level (Böttcher *et al.*, 2011) and globally (Schulze *et al.*, 2012). Additional forest harvests cut the carbon sink of biomass and soil, whereas increasing forest residue harvesting reduces mainly litter and soil carbon stocks (Sievänen *et al.*, 2014). Our results support the conclusions of previous studies that applying the current RED calculation rules to forest harvest residues used in biofuel production or heat and electricity generation overestimates the achievable emission savings (Soimakallio & Koponen, 2011; Koponen *et al.*, 2013). This is because the current RED sustainability criteria for biofuels and bioliquids accounts only for carbon stock changes associated with land-use change (2009/28/EC). There is no change in land-use category when forests are managed sustainably (IPCC, 2006b).

Ensuring the sustainability of bioenergy from forest harvest residues requires accounting for reductions in all carbon pools. Firstly, in addition to acting as carbon reservoirs, soil carbon and organic matter have numerous functions in amending soil structure, water regulation, nutrient cycling, site fertility and biological activity (e.g., Schils *et al*., 2008; Agostini *et al*., 2013). Carbon loss resulting from forest residue harvesting may pose a risk to these functions. Secondly, the inclusion of all carbon stock changes allows a more reliable estimation of the emissions and the potential climate impact of forest bioenergy (Helin *et al*., 2012; Pingoud *et al*., 2012; Repo *et al*., 2012). Comprehensive carbon accounting is crucial because forest-based biomass is estimated to form over 50% of the biomass supply for energy until 2020. The increased demand of forest biomass may be satisfied directly from forest with additional fellings and forest residue harvesting because the available waste wood and wood industry residues are already used for energy production (Fritsche & de Jong, 2013; Scarlat *et al*., 2013).

Currently, the sustainability criteria are set only to biofuels and bioliquids, but the extension of the sustainability requirements to solid and gaseous bioenergy is being planned (COM, 2010; Fritsche & de Jong, 2013; Lamers *et al*., 2013). We show that the current sustainability requirements do not guarantee efficient savings of GHG emissions with forest harvest residue bioenergy. In the long-term forest bioenergy may pave the way for low-emission energy systems, whereas in the short-term, it may even increase GHG emissions because of reductions in forest carbon stocks. These reductions may be compensated by changes in forest management and harvesting practices (Routa *et al*., 2011, 2012; Repo *et al*., 2012; Sathre & Gustavsson, 2012). A regional prioritization of harvest residue extraction, site-specific thresholds for maximum outtake volumes of forest harvest residues and definitions for no-go-areas may decrease risks related to soil productivity and biodiversity (2009/28/EC; Fritsche & de Jong, 2013; Lamers *et al*., 2013). Nevertheless, comprehensive carbon accounting and reliable climate impact estimates of forest bioenergy are needed to determine the amount of additional emission reductions in other sectors to efficiently mitigate climate change.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Comparison of the estimates from different calculation steps to independent data.