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The time aspect of bioenergy – climate impacts of solid biofuels due to carbon dynamics

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Abstract

The climate impacts from bioenergy involve an important time aspect. Using forest residues for energy may result in high initial emissions, but net emissions are reduced over time since, if the residues were left on the ground, they would decompose and release CO_2 to the atmosphere. This article investigates the climate impacts from bioenergy with special focus on the time aspects. More specifically, we analyze the climate impacts of forest residues and stumps where combustion related emissions are compensated by avoided emissions from leaving them on the ground to decompose. These biofuels are compared with fossil gas and coal. Net emissions are defined as emissions from utilizing the fuel minus emissions from a reference case of no utilization. Climate impacts are estimated using the measures radiative forcing and global average surface temperature. We find that the climate impacts from using forest residues and stumps depend on the decomposition rates and the time perspective over which the analysis is done. Over a 100 year perspective, branches and tops have lower climate impacts than stumps which in turn have lower impacts than fossil gas and coal. Over a 20 year time perspective, branches and tops have lower climate impacts than all other fuels but the relative difference is smaller. However, stumps have slightly higher climate impacts over 20 years than fossil gas but lower impacts than coal. Regarding metrics for climate impacts, over shorter time scales, approximately 30 years or less, radiative forcing overestimates the climate impacts compared with impacts expressed by global surface temperature change, which is due to the inertia of the climate system. We also find that establishing willow on earlier crop land may reduce atmospheric CO_2, provided new land is available. However, these results are inconclusive since we haven't considered the effects of producing the agricultural crops elsewhere.

Keywords: bioenergy, climate impacts, forest residues, global average surface temperature, radiative forcing, stumps, time aspects, willow

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Introduction

Bioenergy accounted for approximately 10% (50 EJ) of the total global energy supply (493 EJ) in the year 2008 and is by far the largest renewable energy source (Chum *et al.*, 2011). There is considerable potential to increase this share. In a literature review, Chum *et al.* (2011) concludes that the potential deployment levels of biomass for energy by 2050 could be in the range of 100–300 EJ. Being a renewable fuel, bioenergy is considered a key in global efforts to replace fossil fuels and hereby reduce CO_2 emissions. The European Union has the target of increasing the use of bioenergy and other renewables to at least 20% by the year 2020. In Sweden in the year 2012, renewable energy accounted for 51% of the total energy supply (Swedish Government, 2013). This makes Sweden the EU Member State with the largest share of renewable energy use. In 2005, the use of bioenergy, peat, and waste accounted for 114 TWh, or 25% of the total energy supply (not including losses in nuclear power production). Of this, 73 TWh were by-products from the forest industry, 17 TWh roundwood, 7 TWh forest residues, and 17 TWh consisted of waste, peat, and other biofuels (Swedish Energy Agency, 2006). Stumps constitute a large unused source for bioenergy with considerable potential. The Swedish Forest Agency (2008) estimates that the use of branches and tops can increase to at least 24 TWh yr^{-1} and that the use of stumps can increase to a level of 29 TWh yr^{-1} or more.

When biomass is combusted, the carbon that was once bound in the growing forest is released, thus closing the biogenic carbon cycle. For this reason, bioenergy has often been considered CO_2 neutral. For instance, CO_2-emissions from biofuels are not included in the EU emission trading system (European Commission, 2003). However, bioenergy production may significantly influence biogenic carbon stocks and atmospheric CO_2 in

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either a positive or negative way (IEA, 2010). There is an important time aspect. If a standing tree is harvested and combusted for energy, there will be an instant release of CO_2 to the atmosphere. It may take decades before the new tree has accumulated the same amount of carbon that was emitted during combustion. Removing logging residues for energy, instead of leaving them on the ground, could lead to lower carbon storage in litter and soils (Eriksson & Hallsby, 1992; Ågren & Hyvönen, 2003; Repo *et al*., 2011). Removing stumps would also result in a reduction in the carbon stored in dead organic matter (Melin *et al*., 2010; Walmsley & Godbold, 2010). Vanhala *et al.* (2012) and Repo *et al.* (2012) show that the initial GHG emissions from removing forest residues may be comparable to fossil fuels. But this effect is of transient character. If forest residues or stumps are left on/in the ground, they would decompose and release CO_2 to the atmosphere. Therefore, the climate impact from using forest residues for energy decreases significantly over time since, if they were left in the forest they would decay and release CO_2 (Zetterberg *et al*., 2004; Sathre & Gustavsson, 2011). Repo *et al.* (2011, 2012) and Vanhala *et al.* (2012) point out that the GHG emissions from using forest residues for energy depend on the decomposition rate and the choice of time perspective. Lindholm *et al.* (2010) find that using forest residues for energy is very beneficial for climate mitigation over long time scales. In a 20 year time scale, however, the climate benefits compared with using fossil alternatives are less since the residues are not completely decomposed after 20 years. Melin *et al*. (2010) find that in the long term, burning stumps is a more effective way to reduce emissions than burning coal. However, in the short term, using coal is slightly better than removing stumps from the forest carbon pool. Sathre & Gustavsson (2011) compare the climate impacts (radiative forcing) of forest residues and stumps with fossil fuels and find that over a 240 year time perspective, forest residues are considerably better than using oil, fossil gas, and coal. Over the first 10–25 years, oil and fossil gas have a lower climate impact than forest residues and stumps, but thereafter forest residues and stumps are increasingly superior to fossil alternatives for reducing climate impacts.

The EU commission is in the process of developing sustainability criteria for solid biomass. In 2013, a draft version was made available for interservice consultation (European Commission, 2013). According to this document, proposed sustainable criteria for solid biomass including forest residues requires that at least 60% GHG savings compared to fossil alternatives are reached over a 20 year time horizon. To prioritize between different bioenergy options, decision makers need to understand the temporal aspects of climate impacts of bioenergy. Policies and incentives need to be implemented that encourage sustainable use of bioenergy and replacement of fossil fuels.

The objective of this article is to investigate the climate impacts from bioenergy with a focus on temporal aspects – how their use affects ecosystem carbon stocks over time and the importance of time perspective for the analysis. Special attention is given to how combustion related carbon emissions from forest residues and stumps are compensated by avoided emissions from leaving them on the ground to decompose. We also investigate willow where combustion related emissions are compensated by regrowth and soil carbon accumulation after 3–5 years. Climate impacts of these three solid biofuels are compared with those of fossil gas and coal.

Most studies investigating the climate impacts from biofuels use radiative forcing or derivatives thereof as a measure. This study goes one step further to introduce the measure global average surface temperature as a complementary measure for assessing the dynamic climate effects of emission scenarios.

Materials and methods

System boundaries

A set of solid biofuels has been analyzed, namely branches, tops, and stumps in traditionally managed forests and willow. Branches and tops have faster decomposition rates than stumps and we therefore expect them to differ in terms of their climate impact dynamics. These biofuels are compared to fossil gas and coal. The system boundary of our analysis is illustrated in Fig. 1. Our analysis includes emissions of CO_2, CH_4, and N_2O from the combustion of the fuel and from (fossil) fuel used in equipment for harvest, extraction, and transportation. For willow, N_2O-emissions during growth due to fertilizer use are included. For branches, tops, and stumps, CO_2-emissions from decomposition are included in the reference case. Energy conversion losses, for instance in the production of electricity, are not considered. Nor are substitution effects, such as the avoided emissions when biofuels replace fossil fuels, considered. However, the calculated climate impacts from solid biofuels are compared with those from coal and fossil gas.

In this article, our starting point is a forest stand before harvest. The rationale for this is a hypothetical stand owner's decision to extract forest residues for energy instead of leaving them on the ground to decompose. This leads us to a scenario that starts with an instant release of carbon to the atmosphere, followed by avoided emissions from the reference case of leaving the residues on the ground to decompose. Solid biofuels, in the form of forest residues are produced at $t = 0$. If we instead were to use a starting point after harvest, carbon would first be accumulated for 100 years (in the form of growing branches, tops, and stumps) followed by harvest and release of carbon to the atmosphere. Compared with our chosen staring point, this alternative scenario would result in a one off carbon stock build up which would offset the accumulated emissions downward with

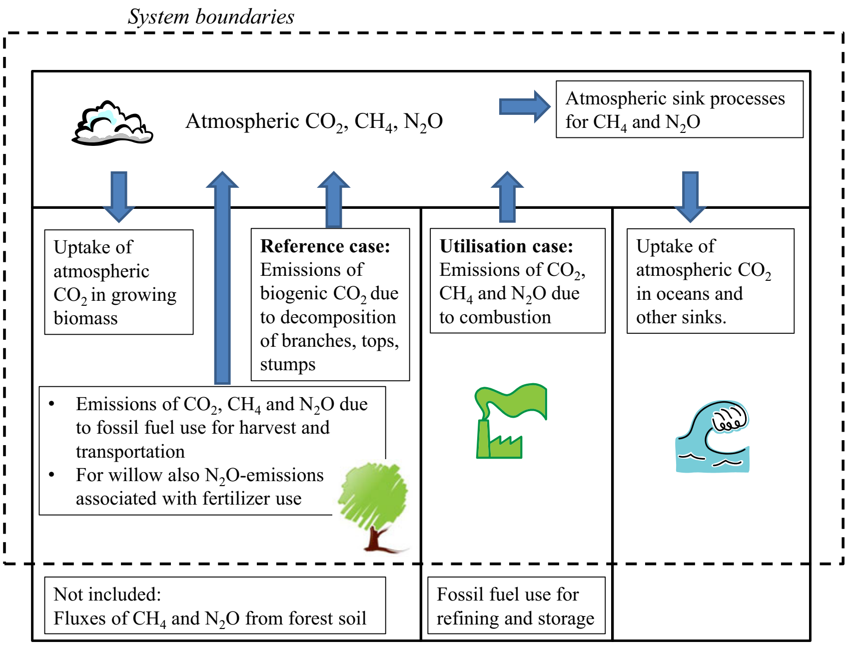

Fig. 1 System boundaries for the investigated solid biofuels.

a constant value. Moreover, the production of forest residues will occur after one full rotation, in our study after 100 years.

We do not apply a true landscape perspective. However, we do analyze a synthetic scenario of 100 identical stands, where the starting point of each stand is shifted 1 year forward in time. In these scenarios, 1 unit of forest residues is produced each year. Although this is not a true landscape perspective, it aims to describe the climate impacts of having a landscape perspective with 100 stands, all at different stages.

Climate impact metrics

The climate impacts from different biofuels have been calculated in four steps:

1. Emissions have been calculated based on data on biogenic carbon stock changes and emission factors
2. Atmospheric concentration changes have been calculated based on emissions
3. Radiative forcing has been calculated based on atmospheric concentration changes
4. Global surface temperature has been calculated based on radiative forcing.

The first three steps follow the same methodology as Zetterberg *et al.* (2004), Holmgren *et al.* (2007), and Kirkinen (2010), while the fourth step, global average surface temperature is calculated with a simpler energy balance model. These methods are described below.

Emissions

In this article, the net emissions, E_{net}, from a biofuel are defined as the emissions from the utilization case minus the emissions from a reference case:

$$E_{\text{net}} = E_U - E_{\text{Ref}} \tag{1}$$

The subscript U refers to the utilization case and Ref to the reference case.

Expression (1) follows recommendations by Schlamadinger *et al.* (1997) and is applied by Zetterberg & Hansén (1998), Kirkinen *et al.* (2008), Hagberg & Holmgren (2008), and Lindholm *et al.* (2010).

Calculated CO$_2$ emissions, $E(t)$ expressed in kg CO$_2$, are based on carbon stock changes, $\Delta S(t)$, also expressed in kg CO$_2$. Assuming that a reduction in an ecosystem's carbon stock results in an immediate emission to the atmosphere, the emissions can be calculated as the carbon stock change, with opposite sign:

$$E(t) = \Delta S(t) = S(0) - S(t) \tag{2}$$

where $S(0)$ is the carbon stock at $t = 0$. Inserting (2) into (1) the net emissions, E_{net}, can be expressed in terms of the carbon stock:

$$E_{\text{net}}(t) = S_{\text{Ref}}(t) - S_U(t) \tag{3}$$

We have here assumed that at $t = 0$, the carbon stock in the reference case is equal to the carbon stock in the utilization case, i.e. SRef(0) = SU(0) The annual net emissions $e_{\text{net}}(t)$, expressed in kg CO$_2$ yr^{-1}, can be calculated as the time derivative of net emissions:

$$e_{\text{net}}(t) = E'_{\text{net}}(t) \tag{4}$$

Finally, the annual CO$_2$ uptake rate, $u(t)$, expressed in kg CO$_2$ yr^{-1}, is defined as the annual emissions with opposite sign:

$$u(t) = -e(t) \tag{5}$$

Atmospheric concentrations

The remaining mass $M_i(t)$ in the atmosphere for gas i at the time t is calculated as:

$$M_i(t) = \int_0^t E_{\text{net},i}(\tau) f_i(t-\tau)d\tau \tag{6}$$

where $f_i(\tau)$ is the pulse response function for greenhouse gas i, as presented by the IPCC (Forster *et al.*, 2007). The pulse response functions for methane (CH_4) and nitrous oxide (N_2O) are described as a single exponential decay function, with average lifetimes of 12 and 114 years respectively. The pulse response function for carbon dioxide is more complex and described by a combination of exponential decay functions:

$$f(t) = 0.217 + 0.259 \cdot e^{-t/172.9} + 0.338 \cdot e^{-t/18.51} + 0.186 \cdot e^{-t/1.186} \tag{7}$$

Based on the remaining mass in the atmosphere, the concentration change $C_i(t)$ at the time t is calculated as:

$$C_i(t) = \frac{M_i(t) \cdot MV_{\text{Atm}}}{M_{\text{Atm}} \cdot MV_i} \tag{8}$$

where MV_{Atm} is the molecular weight of the atmosphere, M_{ATM} is the mass of the atmosphere and MV_i is the molecular weight of gas i.

Radiative forcing

Radiative forcing is a commonly used measure for assessing the expected climate impacts from global emission scenarios. The measure has also been used to assess the expected climate impacts from forest stands and energy carriers (Zetterberg, 1993; Savolainen *et al.*, 1994; Zetterberg *et al.*, 2004; Holmgren *et al.*, 2006, 2007 and Kirkinen *et al.*, 2010; Sathre & Gustavsson, 2011, 2012). Radiative forcing, expressed in W m^{-2}, is described as a change in average net radiation at the top of the troposphere, due to a change in either solar or infrared radiation (IPCC, 1994). This can, for instance, be caused by changes in greenhouse gas concentrations, particles from volcanic eruptions, or changes in solar intensity. A radiative forcing perturbs the balance between incoming and outgoing radiation of the global climate system. A positive radiative forcing tends to warm the surface; a negative radiative forcing tends to cool the surface. Increased concentrations of CO_2 lead to a positive radiative forcing. Ramaswamy *et al.* (2001) describes the relation between radiative forcing and increased concentrations of greenhouse gases in simple GHG specific functions, $RF_i(C_i)$, which are parameterizations of more complex radiative models. For instance, for CO_2, the radiative forcing, RF_{CO2} due to a concentration change $C_{\text{CO2}}(t)$ at the time t is calculated as:

$$RF_{\text{CO2}}(C_{\text{CO2}}) = 5.35\ In\ (C_{\text{CO2}}/C_{\text{CO2,0}}) \tag{9}$$

where $C_{\text{CO2,0}}$ is the reference atmospheric concentration for CO_2, In this article, we use a CO_2 atmospheric concentration value of 360 ppmv.

When several different greenhouse gases, for instance CO_2, CH_4, and N_2O are included in the emission scenario, the total radiative forcing is calculated as the sum of the radiative forcing of each gas, corrected for the overlapping of the infrared absorption bands of CH_4 and N_2O, which is given by Ramaswamy *et al.* (2001).

Often, derivatives of radiative forcing are used, such as:

Absolute global warming potential (AGWP) is the time integration of radiative forcing from when the emission occurs to a prescribed time perspective, for instance 20, 100, or 500 years (Ramaswamy *et al.*, 2001).

$$\text{AGWP}(t) = \int_0^t \text{RF}(\tau)d\tau \tag{10}$$

Absolute global warming potential is expressed in J m^{-2} or W yr m^{-2}, where the term year refers to the number of seconds in 1 year. AGWP is also referred to as accumulated radiative forcing(Zetterberg *et al.*, 2004; Holmgren *et al.*, 2006, 2007) or cumulative radiative forcing (CRF) (Kirkinen, 2010; Sathre & Gustavsson, 2011). The term Instantaneous radiative forcing, expressed in W m^{-2}, is sometimes used to distinguish radiative forcing from accumulated radiative forcing. Global Warming Potentials (GWP) are weighting factors used to express the emission of 1 kg of a GHG gas in the equivalent CO_2-emission. The GWP-factor for gas i over the time perspective T is calculated as $\text{AGWP}_i(T)$ for the unit emission of 1 kg of gas i, divided by $\text{AGWP}_{\text{CO2}}(T)$ for the release of 1 kg CO_2. In this article, we use GWP-factors over a 100 year perspective, which are 25 for CH_4 and 298 for N_2O (Forster *et al.*, 2007), to present CO_2-equivalent emissions in Figs 3a, d and 4a. However, all radiative forcing calculations in this paper are based on emissions of CO_2, CH_4, and N_2O without GWP-factors. The Relative Radiative Forcing Commitment, RRFC*(t)*, is described by Kirkinen *et al.* (2008) as the ratio of the energy absorbed in the Earth climate system due to changes in greenhouse gas concentrations compared to the energy released at the combustion of the fuel. It is calculated as:

$$\text{RRFC}(t) = \frac{\text{AGWP}(t) \cdot A}{E_{fu}} \tag{11}$$

where A is the surface of the Earth, $5.10 \cdot 10^8$ km^2 (Central Intelligence Agency, 2013) and E_{fu} is the energy content of the fuel used. A RRFC of 1.0 corresponds to an accumulated radiative forcing of 2.0 J m^{-2} PJ^{-1} fuel or 0.062 μW yr m^{-2} PJ^{-1} fuel.

Global average surface temperature

Based on radiative forcing, global average surface temperature is calculated using analytical functions from a with a simpler energy balance model. The increased concentration of CO_2 creates a radiative forcing, ΔQ, which drives the climate system to a new equilibrium. The dynamic response of global average surface temperature due to a forcing can be approximated by the equation:

$$mc\frac{d}{dt}T = -\beta(T - T_{\text{old\_equilib}}) + \Delta Q \tag{12}$$

where T is the global average surface temperature, mc is the heat capacity of the climate system, and β is the climate feedback parameter:

$$\beta \Delta T = \Delta Q \qquad (13)$$

and where ΔT is the difference between the old and new equilibrium temperatures:

$$\Delta T = T_{\text{new equilib}} - T_{\text{old equilib}} \qquad (14)$$

And by inserting (13) into (14):

$$T_{\text{new equilib}} = T_{\text{old equilib}} + \Delta Q/\beta \qquad (15)$$

Solving Eqn (12) yields the dynamic temperature response:

$$T(t) = T_{\text{new equib}} - \Delta T * e^{-t\beta/mc} \qquad (16)$$

A value for the e-folding time mc/β has been approximated by studying the e-folding time for a control run of a General Circulation Model, the Planet simulator (Planet Simulator, 2011), due to a CO_2 pulse. Inspection of the temperature response to an induced forcing yielded an e-folding time of approximately 8.4 years.

In General Circulation Models, the climate sensitivity parameter λ ($=\beta^{-1}$) is usually in the range of $\lambda = 0.5$–1.2 K $m^{-2}W^{-1}$(IPCC, 2007). This corresponds to a β in the range of 0.83–2.0 K^{-1} Wm^{-2}. In this paper, we assume a default value of $\beta = 1.0$ $K^{-1}Wm^{-2}$.

With an e-folding time of 8.4 years, this gives us a value for the system heat capacity, mc = $\beta \times 8.4$ years = 26.6 MJ K^{-1} m^{-2}. For illustration, an equivalent heat capacity would be achieved by a combination of the atmosphere (m = 1300 kg m^{-2}, c_p = 1004 J kg^{-1} K^{-1}) plus 63 m of the ocean (m = 63 000 kg m^{-2}; c_v = 4218 J kg^{-1} K^{-1}). This e-folding time appears reasonable, since the mixed layer of the ocean is well adjusted to the atmosphere (over a time scale of some months); is approximately 100 meters deep; and the fact that the ocean corresponds to 70% of the Earth's surface.

The dynamic temperature response, dT is calculated by the model for each time step dt. For this purpose, Eqn (12) was rewritten on the form:

$$dT = dt \cdot \frac{1}{mc}\left[\Delta Q - \beta(T - T_{\text{old\_equilib}})\right] \qquad (17)$$

The following examples may facilitate the translation between emissions, radiative forcing, and temperature. If 1 kton CO_2 is released at t = 0, the corresponding accumulated radiative forcing will be 0.13 μW yr m^{-2} after 100 years and the temperature change will be 1.0 nK after 100 years. If 1 kton CO_2 is released each year for 100 years, the corresponding instant radiative forcing will be 0.13 μW m^{-2} after 100 years and the temperature change will be 0.12 μK after 100 years (values derived in this paper).

Investigated fuels and input data

The investigated fuels and data on carbon stock changes are summarized in Table 1.

Data on carbon stock changes due to the decomposition of branches, tops, and stumps from Norway Spruce (*Picea Abies*) in Sweden are based on the dynamic soil carbon model *Q*-model (Ågren G I (2011) Personal communication, Eliasson *et al.*, 2013). The model simulates the development of carbon stocks (soil and trees) for a Norway Spruce forest at Växjö, assuming three different management regimes:

- A reference case with no extraction of branches, tops, or stumps;
- Branches and tops: 80% of branches and tops are removed at each harvest,
- Branches, tops, and stumps: 80% branches and tops are removed at each harvest and 50% of the stump-coarse root system at final harvest.

At each harvest event, there are three types of biomass fractions available. The largest fraction consists of logged trees and corresponds to approximately 109 MgC ha^{-1}. If 80% of the branches and tops are extracted, this fraction corresponds to approximately 35 MgC ha^{-1} and if, in addition, 50% of the stumps-coarse root system are extracted, these correspond to an additional 24 MgC ha^{-1}. Remaining biomass in the forest (20% branches and tops, 50% stumps-coarse roots, and 100%

Table 1 Fuels investigated in this paper.

S.No	Investigated fuel	Reference case
1.	Branches and tops Sweden (*Q*-model). Branches and tops from a spruce forest in southern Sweden are extracted for energy. Estimates are based on the dynamic soil carbon *Q*-model (Ågren 2011; Eliasson *et al.*, 2013).	Decomposition of residues
2.	Branches Finland (Yasso). Forest residues in the form of branches from southern Finland are extracted for energy. Estimates are based on the dynamic soil carbon model, *Yasso07* (Repo *et al.*, 2011)	Decomposition of residues
3.	Stumps Sweden (*Q*-model). Stumps from a spruce forest in southern Estimates are based on the *Q*-model (Ågren 2011; Eliasson *et al.*, 2013)	Decomposition of residues
4.	Stumps Finland (Yasso). Stumps from southern Finland are extracted for energy. Estimates are based on the Yasso07-model (Repo *et al.*, 2011).	Decomposition of residues
5.	Willow Sweden (*Q*-model). Willow is assumed to be produced on land previously used for crop production. Estimates are based on the *Q*-model (Ågren 2011; Eliasson *et al.*, 2013).	Continued crop production with no net soil carbon changes
6.	Fossil gas, used as a benchmark for comparison	–
7.	Coal, used as a benchmark for comparison	–

fine roots) corresponds to approximately 71 MgC ha^{-1}. In this paper, the climate impacts from using branches, tops, and stumps for energy have been analyzed. However, the potential use of logged wood for energy has not been analyzed. The model simulations do not include thinning events. While thinning events are common in real forest practices, omitting them allows us to isolate the effects of producing bioenergy at $t = 0$. Including thinning events would complicate the analysis since bioenergy is produced at several occasions over a rotation period.

Data on net carbon stock changes from the decomposition of branches (diameter 2 cm) and stumps (diameter 26 cm) from Norway Spruce (*Picea Abies*) in Finland have been simulated by the dynamic soil carbon model *Yasso07* (Repo *et al.*, 2011).

Data on carbon stock changes when establishing willow (*Salix*) on earlier crop land are based on carbon stock changes simulated by the *Q*-model (Ågren 2011; Eliasson *et al.*, 2013).

Comparison of Yasso07 and the Q-model

The central concept of the *Q*-model is the quality of the organic matter of the soil (hence the name *Q*) which varies between litter fractions and changes gradually over time. Litter enters the soil in litter fractions that originate from needles, branches, stems, fine roots, stumps, and underground vegetation. The microbial community causes decomposition processes which are described by model functions and parameters. These functions and parameters are empirically determined.

The Yasso07 model consists of four compound groups: waxes etc., sugars etc., cellulose etc., and lignin etc. Litter in the form of leaves, branches, roots, stems, and stumps enter into these groups. Decomposition rates depend on temperature and precipitation and have been empirically determined. As the model executes through the time steps decomposition results in mass flows between the compound groups and the formation of humus.

Yasso07 and *Q* have been used in a common project to simulate how Sweden's forest carbon pool has developed between 1926 and 2000. The model results were compared with carbon pool measurements done during 1994–2000. The results from the models agreed well with measured data, although the annual variability between the three methods was significant mainly due to different assumptions regarding annual climate variation (Ortiz *et al.*, 2009). The authors conclude that both models are particularly useful for soil carbon projections.

Emission factors

CO_2-emission factors for the combustion of forest residues show considerable variability. Zetterberg & Hansén (1998) present a range from 95–115 g MJ^{-1} for branches and tops; Repo *et al.* (2011) use 94.4 g MJ^{-1}; while Kirkinen *et al.* (2008) apply 109.6 g MJ^{-1}. For stumps, Repo *et al.* (2011) use 95.0 g MJ^{-1}; while Melin *et al.* (2010) use 95.4 g MJ^{-1}.

The variability in emission factors is mainly due to different assumptions of water content which affects the calorific heating values. Assuming a high water content would result in higher emission factors and consequently higher climate impacts. However, power plants with flue gas condensation equipment can recover some of the heat energy bound in the water vapor. In this paper, we use emission factors of 98.0 g CO_2 $MJ^{-1}{}_{fuel}$ for branches and tops, 97.5 CO_2 $MJ^{-1}{}_{fuel}$ for stumps and 98.9 CO_2 $MJ^{-1}{}_{fuel}$ for willow. This is based on elementary analysis of the fuels and corresponds to calorific heating values (dry and ash free) of 19.9 MJ kg^{-1} fuel for branches and tops, 19.5 MJ kg^{-1} fuel for stumps and 18.1 MJ kg^{-1} fuel for willow; and carbon contents (dry and ash free) of 53.1% for branches and tops, 51.8% for stumps, and 48.9% for willow (Strömberg & Herstad Svärd, 2012).

Emissions related to harvest and transportation of branches and tops are estimated to be 1.9 g CO_2 MJ^{-1}, 0.14 mg CH_4 MJ^{-1}, and 0.06 mg N_2O MJ^{-1}, and for stumps 2.6 g CO_2 MJ^{-1}, 0.29 mg CH_4 MJ^{-1}, and 0.09 mg N_2O MJ^{-1}. For willow, emissions related to growth, harvest, and transportation are estimated to be 3.7 g CO_2 MJ^{-1}, 3.3 mg CH_4 MJ^{-1}, and 19 mg N_2O MJ^{-1}, which includes N_2O from fertilizer use (Börjesson, 2006). For all biofuels, (branches, tops, stumps and willow) emissions of CH_4 and N_2O related to combustion are estimated to be 30 mg CH_4 MJ^{-1} and 6 mg N_2O MJ^{-1} (Naturvårdsverket, 2013). For fossil gas, emissions related to the production and distribution are estimated to be 5.5 g CO_2 MJ^{-1}, 275 mg CH_4 MJ^{-1}, and $2.6{\cdot}10^{-12}$ g N_2O MJ^{-1} (Gode *et al.*, 2011). For the combustion of fossil gas, we use 56.8 g CO_2 MJ^{-1} (Gode *et al.*, 2011). For coal, emissions related to production and transportation are estimated to be 6.5 g CO_2 MJ^{-1}, 8.8 mg CH_4 MJ^{-1}, and 0.13 mg N_2O MJ^{-1}, while combustion related emissions are estimated to be 99 g CO_2 MJ^{-1}, 2.2 mg CH_4 MJ^{-1}, and 1.1 mg N_2O MJ^{-1} (Vattenfall, 2008). Emission factors for all fuels and GHG-gases are summarized in Table 2.

Results

Illustration of how net CO_2 emissions are calculated from carbon stock changes

For illustration, Fig. 2 shows how net emissions are calculated from carbon stock changes and the role of the reference case. Tops and branches from a spruce forest in southern Sweden have been used as an example. The reference case is when the forest residues are left in the soil to decompose naturally (top curve). The utilization case is when the residues are harvested (second curve from the top). The net emissions (bottom curve) have been calculated as the difference between the reference case and the utilization case. The graph shows how the net emissions are reduced over time approaching zero.

Calculated emissions, radiative forcing, and temperature change for different biofuels

Emissions and climate impacts for different fuels, assuming the single use of 1 PJ fuel at $t = 0$, have been calculated and presented in Fig. 3a, c. Fig. 3a shows net greenhouse emissions from different fuels, expressed

Table 2 Summary of emission factors for the studied fuels does not include the avoided emissions from the reference case, which are time dependent.

Fuel and stage	CO_2 [g $MJ^{-1}{}_{fuel}$]	CH_4 [mg $MJ^{-1}{}_{fuel}$]	N_2O [mg $MJ^{-1}{}_{fuel}$]	Reference
Branches and tops				
Harvest, transports	1.9	0.14	0.06	Lindholm *et al.* (2010)
CO_2 from combustion	98.0			Strömberg & Herstad Svärd (2012)
CH_4, N_2O combustion		30	6	Naturvårdsverket (2013)
Stumps				
Harvest, transports	2.6	0.29	0.09	Lindholm *et al.* (2010)
CO_2 from combustion	97.5			Strömberg & Herstad Svärd (2012)
CH_4, N_2O combustion		30	6	Naturvårdsverket (2013)
Willow				
Growth, harvest, tpt	3.7	3.3	19	Börjesson (2006)
CO_2 from combustion	98.9			Strömberg & Herstad Svärd (2012)
CH_4, N_2O combustion		30	6	Naturvårdsverket (2013)
Fossil gas				
Production, distribution	5.5	275	$2.6 \cdot 10^{-9}$	Gode *et al.* (2011)
Combustion	56.8	–	–	Gode *et al.* (2011)
Coal				
Production, transports	6.5	8.8	0.13	Vattenfall (2008)
Combustion	99.0	2.2	1.1	Vattenfall (2008)

in g CO_2-equivalents using GWP_{100}-values to include expected climate impacts from CH_4 and N_2O. Over a 100 year perspective, we estimate GHG emissions to be 7–10 g CO_2-equiv. MJ^{-1} for branches and tops, 8–31 g CO_2-equiv. MJ^{-1} for stumps, 69 g CO_2-equiv. MJ^{-1} for fossil gas, and 106 g CO_2-equiv. MJ^{-1} for coal. This can be compared with the carbon content in forest residues which is approximately 100 g CO_2 MJ^{-1}. Emissions related to harvest/extraction and transports are estimated to be 1.9 g CO_2-equiv. MJ^{-1} for branches and tops, 2.6 g CO_2-equiv. MJ^{-1} for stumps, 12.4 g CO_2-equiv. MJ^{-1} for fossil gas, and 6.8 g CO_2-equiv. MJ^{-1} for coal. Emissions from CH_4 and N_2O are estimated to be 2.6 g CO_2-equiv. MJ^{-1} for branches, tops, and stumps, 6.9 g CO_2-equiv. MJ^{-1} for gas, and 0.6 g CO_2-equiv. MJ^{-1} for coal. It takes 3–7 years before branches and tops and 17–18 years before stumps have lower total emissions than fossil gas. In Fig. 3a, the emission curves remind of exponential decay approaching zero in an asymptotic manner. For all forest residues (branches, tops and stumps), there is an initial emission pulse at $t = 0$, due to combustion, which is reduced over time due to avoided emissions from decomposition in the reference case. For fossil gas and coal, there is of course no uptake or avoided emissions, explaining why the emissions are constant over time.

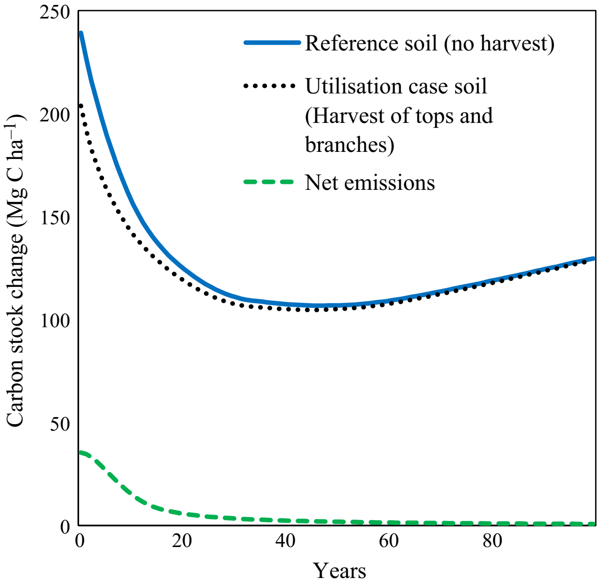

Fig. 2 Illustration of how net biogenic emissions are calculated as carbon stock changes from the reference case (no harvest) minus carbon stock changes from the utilization case (harvest of branches and tops). Data from Ågren (2011).

Based on emissions estimates, corresponding accumulated radiative forcing is calculated and presented in Fig. 3b. Over 100 years, we estimate the accumulated radiative forcing to be 2.1–2.8 μW yr m^{-2} PJ^{-1} for branches and tops, 3.8–6.0 μW yr m^{-2} PJ^{-1} for stumps, 8.7 μW yr m^{-2} PJ^{-1} for fossil gas, and 13.8 μW yr m^{-2} PJ^{-1} for coal. It takes 4–9 years before branches and tops and 27–28 years before stumps have lower accumulated radiative forcing than fossil gas.

Based on radiative forcing, global surface temperature change has been calculated and is presented in Fig. 3c. Over 100 years, the average temperature change is estimated to be 21–28 nK PJ^{-1} for branches and tops,

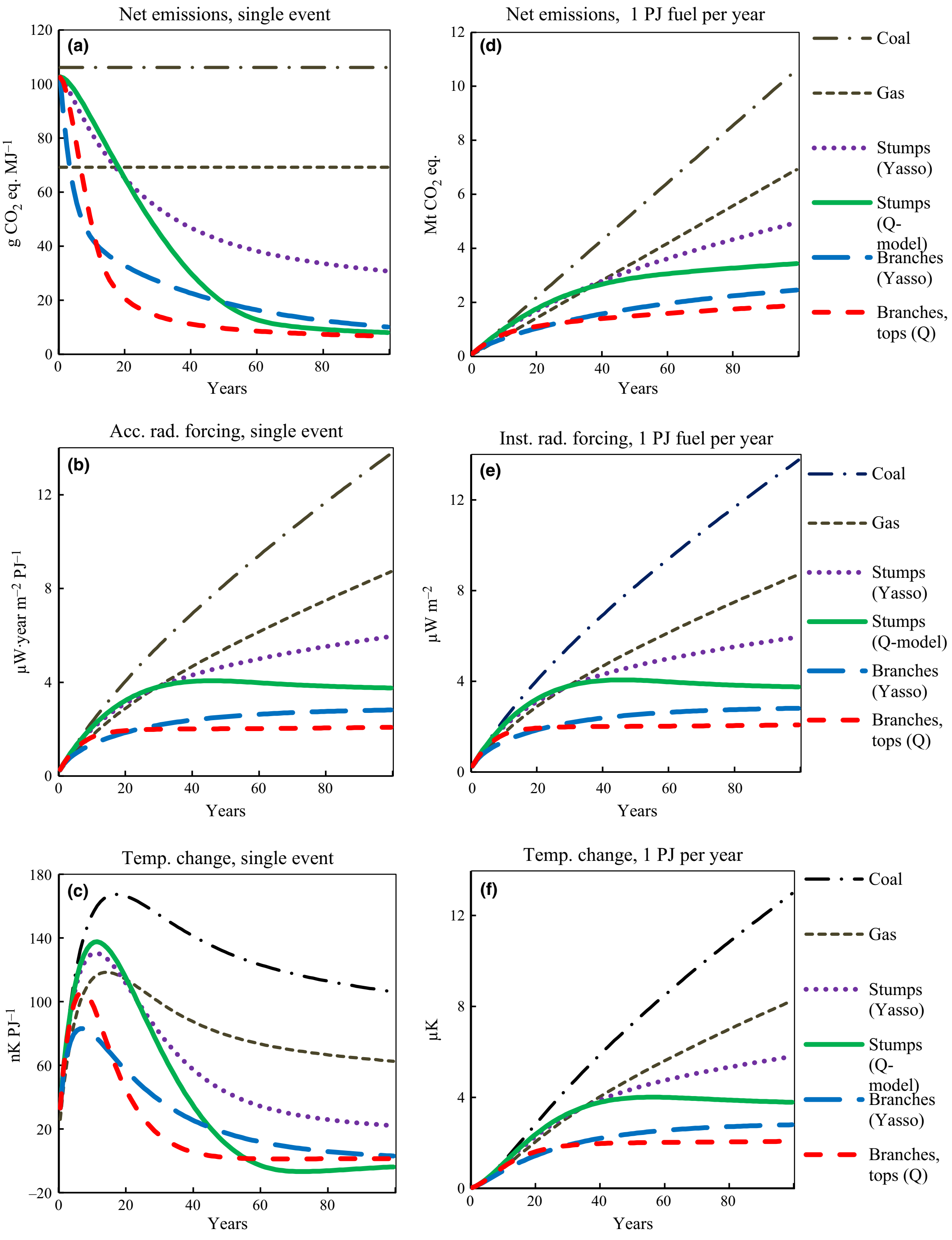

Fig. 3 Climate impacts from fuels representing different decomposition rates. Fig. 3a, c show climate impacts from using 1 PJ of fuel at a single event at $t = 0$, expressed as emissions in Fig. 3a; accumulated radiative forcing in Fig. 3b; and temperature change in Fig. 3c. Fig. 3d, f show climate impacts from continuous use of 1 PJ per year, expressed as emissions in Fig. 3d, instantaneous radiative forcing in Fig. 3e and temperature change in Fig. 3f. Positive values correspond to warming and negative values to cooling. Accumulated radiative forcing is given in the unit μW yr m^{-2}/PJ, where 'year' refers to the number of seconds in one year. Tabled values at $t = 20$ and $t = 100$ are presented in Appendix S1.

38–58 nK PJ^{-1} for stumps, 83 nK PJ^{-1} for fossil gas, and 130 nK PJ^{-1} for coal. It takes 6–12 years before branches and tops and 35 years before the average temperature change from using stumps is lower than that from fossil gas.

In Fig. 3c, the curves show an increased temperature followed by a decrease in temperature. The reason for this is that the temperature is driven by the radiative forcing, but due to the inertia of the climate system, it takes time for the temperature to fully respond to a forcing. The reduction in temperature beyond 20 years is due to a decreased forcing.

Emissions and climate impacts for different fuels, assuming the continuous use of 1 PJ fuel yr^{-1}, have been calculated and presented in Fig. 3d, f. Fig. 3d shows net emissions from different fuels, expressed in Mt CO_2-equivalents. Based on these emissions, corresponding instantaneous radiative forcing is presented in Fig. 3e and surface temperature change is presented in Fig. 3f.

Note that in Fig. 3b, the measure accumulated radiative forcing is used to describe the climate impacts from a single fuel event, while in Fig. 3e, the measure instantaneous radiative forcing is used to describe the climate impacts for the continuous use of 1 PJ fuel yr^{-1}. As a result, Fig. 3b and Fig. 3e have identical shape.

Willow

Willow differs from forest residues (branches, tops, and stumps) in an important way. Forest residues are produced from land already established for forest production. The reference case is a scenario where the residues are left to decay naturally. Therefore, using forest residues for energy results in net emission compared to the reference case. In contrast, willow is usually established on arable land which has earlier been used for crops. According to simulations by Ågren (2011), the establishment of willow will increase the total carbon per area unit as compared to crops. So, using willow for energy causes a net CO_2 uptake compared with the reference case of crops. This puts willow at a significant advantage compared to forest residues, but requires additional land. Fig. 4a, c show estimated emissions, radiative forcing, and global average surface temperature change for the production, on average, of 1 PJ willow per year for 100 years, with crops as the reference scenario. The jaggedness of the willow curve is due to repeated growth and harvest periods with 3–5 year intervals. For comparison, corresponding emissions, radiative forcing, and temperature is calculated for the production and use of 1 PJ fossil gas and coal per year for 100 years. Based on these calculations, we estimate greenhouse gas emissions for willow over a 100 year perspective to be negative, −2.0 g CO_2-equiv. MJ^{-1} as compared to +69 g CO_2-equiv. MJ^{-1} for fossil gas, and +106 g CO_2-equiv. MJ^{-1} for coal. We estimate the instant radiative forcing after 100 years to be −0.2 μ W m^{-2} for willow as compared to +8.7 μ W m^{-2} for fossil gas and +13.8 μ W m^{-2} for coal. Further, we estimate the temperature change after 100 years to be −0.05 μK for willow, + 8.3 μK for fossil gas and +13 μK for coal.

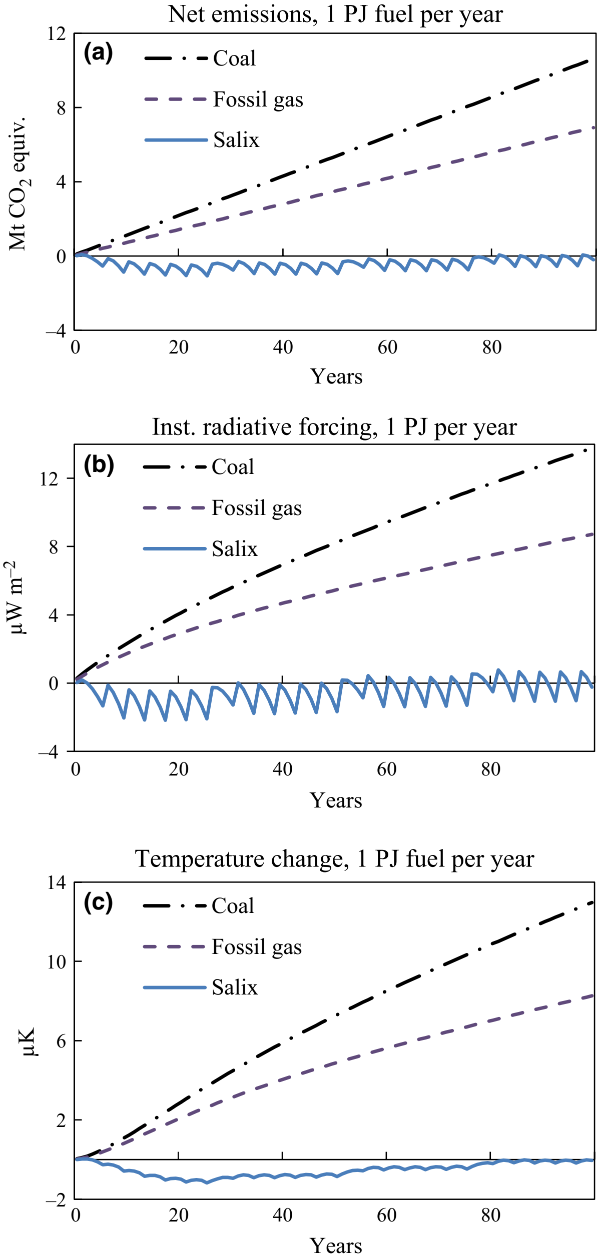

Fig. 4 Climate impacts from producing willow for energy, with crops as the reference scenario. Fig. 4a shows net emissions, Fig. 4b instant radiative forcing and Fig. 4c temperature change. Impacts from using the corresponding amount of fossil gas and coal are shown for comparison.

Discussion

We find that the climate impacts from the use of branches, tops, and stumps depend on how fast the combustion related emissions are compensated by avoided emissions from leaving them on the ground to decompose. For branches and tops (relatively fast decomposition), we estimate greenhouse gas emissions over a 100 year perspective to be 7–10 g CO_2 equiv. MJ^{-1}, while for stumps (relatively slow decomposition), greenhouse gas emissions over a 100 year perspective are 8–31 g CO_2 equiv. MJ^{-1}. Our results in large, confirm other previous studies. Schlamadinger *et al.* (1995), estimate that CO_2-emissions over a 100 year perspective for branches and tops range between 9 and 26 g CO_2 MJ^{-1}. Corresponding values from Wihersaari (2005) are 11–12 g CO_2 MJ^{-1} and from Kujanpää *et al.* (2010) 17 g CO_2 MJ^{-1}. Repo *et al.* (2011) estimate CO_2-emissions over a 100 year perspective to be 2–16 g CO_2 MJ^{-1} for branches and 18–27 g CO_2 MJ^{-1} for stumps. Lindholm *et al.* (2010) estimate average CO_2-emissions over 100 years to be 20 g CO_2 MJ^{-1} for branches and tops and 37 g CO_2 MJ^{-1} for stumps. We estimate the accumulated radiative forcing over 100 years for branches and tops to be 2.1–2.8 μW yr m^{-2} PJ^{-1} fuel. Holmgren *et al.* (2007) estimate the accumulated radiative forcing over 100 years for branches and tops to be 1.6–2.6 μW yr m^{-2} PJ for branches and tops fuel (values recalculated from continuous fuel use). Kirkinen *et al.* (2008) estimate the RRFC for forest residues to be 20–40, which corresponds to an accumulated radiative forcing of approximately 1.2–5.0 μW yr m^{-2} PJ^{-1} fuel.

We find that the time perspective over which the analysis is done is critical for the estimated climate impact of biofuels. Our results show that over a 100 year perspective, branches and tops are significantly better for climate mitigation than stumps which in turn are significantly better than fossil gas and coal. Over a 20 year time perspective, branches and tops have lower climate impacts than all other fuels but the relative is smaller. Over 20 years however, stumps have lower climate impacts than coal, but slightly higher impacts than fossil gas.

The temporal aspects of the climate impacts of bioenergy may have implications from a policy point of view. Given the urgency of climate mitigation, fuels that are beneficial over 20–30 years or less are particularly interesting for policy makers. Our results indicate that forest residues with fast decomposition rates, for instance branches and tops, are better options for reducing global greenhouse gas emissions over 20–30 years than those with slower decomposition rates, such as stumps. Over 20 years, fossil gas has slightly lower climate impacts than stumps. Over 100 years however, stumps are clearly a better mitigation option than fossil gas. This illustrates a political dilemma of balancing short term benefits of some fuels with long term benefits of others.

If environmental legislation, for instance the EU sustainability criteria for solid biomass, requires that climate impacts from biofuels are calculated over 20 years, this would put forest residues and especially stumps at a disadvantage vis-à-vis fossil alternatives.

We find that establishing willow may result in a net accumulation of carbon in the soil and a net uptake of atmospheric carbon compared to the reference case of crops. This means that from a climate mitigation point of view, willow may have a significant advantage compared to forest residues, provided that new land is available. However, there are other aspects that need to be considered. Firstly, the benefit of willow over forest residues is mainly due to the carbon sequestration in the soil. After some years, a new equilibrium amount of soil carbon will be reached, and the benefit of additional crops reduced. Secondly, there may be other bioenergy systems with similar characteristics as willow leading to a net accumulation of carbon in the soil. Fig. 5 illustrates the carbon stock changes for three different land use options: crops, willow and Norway spruce. The figure shows that establishing spruce will also increase the carbon stock as compared to crops. Moreover, spruce will after 30 years surpass willow in terms of carbon stock. The question of which biofuel, willow or spruce, is best for climate mitigation is beyond the scope of this paper, but it's likely that establishing spruce will create larger carbon pools than willow, but produce biofuels much later. Thirdly, since willow or a new spruce forest replaces crops, a relevant question to ask is how the crops are replaced. If the replaced crops are produced elsewhere through intensified agriculture or on new agricultural land, the analysis of the climate effects of

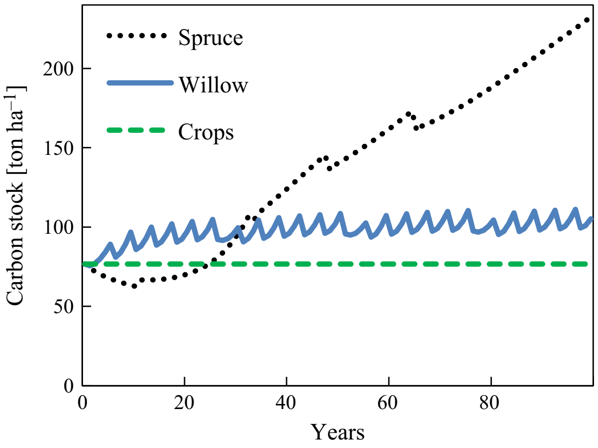

Fig. 5 Carbon stock changes for three different options of land use; crops, willow and Norway spruce.

willow should also include the net effects of relocating the crops. Such an expanded analysis has not been performed in our study. These aspects make it difficult to compare the climate impacts of willow with those from branches, tops, and stumps.

The choice of reference scenario is critical for the estimated climate impacts. Our analysis starts when the forest residues were extracted, not when the trees were planted. One may argue that the growth stage should be included in the analysis, since if there is no growth, there cannot be emissions. The typical situation in Sweden is that forests have long been used for the production of timber and cellulose for the pulp and paper industry. Forest residues from loggings are often collected and used as energy. The point of departure for our analysis is the decision to extract forest residues for energy instead of leaving them on the ground to decompose. Using the residues for energy will result in net emissions compared to leaving them on the ground and the consequent climate impacts have been analyzed.

In this study, GHG-emissions from fossil fuel use related to harvest, collection, and transportation are estimated to be 1.9 g CO_2 MJ^{-1} for branches and tops and 2.7 g CO_2 MJ^{-1} for stumps (Lindholm *et al.*, 2010). Other studies estimate these emissions to be between 1.1 and 3.5 g MJ^{-1} (Zetterberg *et al.*,2004; Wihersaari, 2005; Kirkinen, 2010), which can be compared with the carbon content of biofuels of approximately 100 g CO_2 MJ^{-1}. In this study, emissions of CH_4 and N_2O from the combustion of solid biofuels are estimated to be 2.6 g CO_2 equiv. MJ^{-1}. Wihersaari (2005) and Lindholm *et al.* (2010) estimated the climate effects from combustion related methane and nitrous oxide to be approximately 2 g CO_2 equiv. MJ^{-1}. For fossil gas, emissions related to the production and distribution is estimated to be 12.4 CO_2 equiv. MJ^{-1}, which is due to significant CH_4-leakage in transport and distribution networks and correspond to EU conditions. Energy conversion losses, for instance in the production of heat or electricity, has not been considered in this study. Substitution effects, such as avoided emissions from fossil fuel use, are not included. However, these can be assessed by comparing the different fuels in Fig. 3 and Fig. 4.Whether extraction of branches, tops, and stumps will affect forest production in the next forest generation has not been analyzed.

We have used three types of metrics (emissions, radiative forcing, or temperature) for assessing the climate impacts. We find that radiative forcing and temperature change can both be used for assessing the time dependent climate impacts of biofuels due to their carbon dynamics. But there are important differences. Temperature change provides a more direct measure for climate impacts. Over shorter time scales (up to approximately 30 years), radiative forcing overestimates the impact compared with that expressed by global surface temperature change, which is due to the inertia of the climate system. Given the need to reduce global emissions on a time scale shorter than 30 years, it is important that analytical tools can describe impacts over 30 years or less in an adequate way. This suggests that for medium term emission scenarios, over 30 years or less, global surface temperature change provides a more relevant description of expected climate impacts than radiative forcing. This insight could affect the conclusions of other studies. For instance, Sathre & Gustavsson (2011) use cumulative (accumulated) radiative forcing to show that forest residues have a larger climate impact than fossil gas and oil over the first 10–25 years, but a lower climate impact thereafter. We find that by using average temperature change as a metric instead of accumulated radiative forcing, it takes approximately 5 years more before forest residues and stumps have lower climate than fossil gas. However, calculating temperature change involves uncertainties, mainly related to the climate sensitivity and heat capacity of the atmosphere-ocean system. A detailed sensitivity analysis of the energy balance (temperature) model is provided in Zetterberg & Chen (2011). This analysis shows that uncertainties regarding the climate sensitivity and heat capacity of the climate model lead to significant uncertainties in the calculated absolute values of global average surface temperature change. However, the relative differences among different fuels considered are not that sensitive to these factors as long as the same model is used. We further observe that our simpler energy balance model can reasonably well capture the main features of the temperature response calculated by a much more advanced General Circulation Model, both with regard to the main dynamic features, as well as their timing and amplitude.

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Supporting Information

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

Appendix S1. Values from Fig. 3. Tabled values from Fig 3 showing climate impacts for different fuel types expressed as net emissions, radiative forcing and global average surface temperature.