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The role of forest residues in the accounting for the global warming potential of bioenergy

GEOFFREY GUEST*, FRANCESCO CHERUBINI* and ANDERS HAMMER STRØMMAN*

Department of Energy and Process Engineering, Norwegian University of Science & Technology, Trondheim, Norway

Abstract

Bioenergy makes up a significant portion of the global primary energy pie, and its production from modernized technology is foreseen to substantially increase. The climate neutrality of biogenic CO_2 emissions from bioenergy grown from sustainably managed biomass resource pools has recently been questioned. The temporary change caused in atmospheric CO_2 concentration from biogenic carbon fluxes was found to be largely dependent on the length of biomass rotation period. In this work, we also show the importance of accounting for the unutilized biomass that is left to decompose in the resource pool and how the characterization factor for the climate impact of biogenic CO_2 emissions changes whether residues are removed for bioenergy or not. With the case of Norwegian Spruce biomass grown in Norway, we found that significantly more biogenic CO_2 emissions should be accounted towards contributing to global warming potential when residues are left in the forest. For a 100-year time horizon, the global warming potential bio factors suggest that between 44 and 62% of carbon-flux, neutral biogenic CO_2 emissions at the energy conversion plant should be attributed to causing equivalent climate change potential as fossil-based CO_2 emissions. For a given forest residue extraction scenario, the same factor should be applied to the combustion of any combination of stem and forest residues. Life cycle analysis practitioners should take these impacts into account and similar region/species specific factors should be developed.

Keywords: Bioenergy, Biomass, Carbon Neutral, Climate Change, Forest Residues, Life Cycle Assessment

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Introduction

Bioenergy constitutes roughly 10% and 78% of the world's primary and renewable energy, respectively, while fossil energy makes up close to 80% of our primary energy consumption (Cullen & Allwood, 2010). As we move forward with an effort to replace this fossil energy with renewables, there are active policies around the world calling for significant increases in bioenergy production where most of these policies consider the CO_2 emitted from sustainably growing biomass as climate neutral (EU, 2008; Morgera *et al.*, 2009; Pous, 2009; Beurskens *et al.*, 2011). Attributing zero climate impact potential to such emissions has been widely popularized throughout the recent past (Cherubini & Strømman, 2011). It is the current assumption specified by the intergovernmental panel on climate change (IPCC) when accounting for CO_2 emissions from bioenergy sources, where they state that such emissions should be reported as an information item, but it should not be included in the national greenhouse emissions account (IPCC 2006). This is to avoid double counting where carbon stock changes are reported in the agricultural, forestry and other land-use sector.

Correspondence: Geoffrey Guest, Norwegian University of Science & Technology, Department of Energy and Process Engineering, Industrial Ecology Programme, Høgskoleringen 5 (E1), 7491 Trondheim, Norway, tel. + 47 735 93988, fax + 47 735 98943, e-mail: geoffrey.guest@ntnu.no

From a life cycle assessment (LCA) perspective, bioenergy systems continue to be analysed in large numbers where a recent article (Cherubini & Strømman, 2011) found that all but one of the 94 studies that they reviewed did not consider climate impact associated to the CO_2 emissions derived from the renewable biomass. In other words, most studies to date are fixed within the carbon neutral-equals-climate neutral paradigm (Guest *et al.*, 2012). This paradigm means that so long as CO_2 emissions are coming from biomass that is assumed to be re-grown within the given biomass rotation period, then the radiative forcing effects due to these emissions can be assumed negligible. This was found to be a sensible assumption for biomass with quick rotation periods (like annual crops), but this simplification does not hold for longer rotation periods especially for boreal forest biomass which have rotation periods commonly hovering around 100 years (Cherubini *et al.*, 2011a).

Recent work has suggested a way to quantify these impacts where they termed and defined the GWP_{bio} (global warming potential) factor (Cherubini *et al.*, 2011a). This factor can be directly multiplied by the CO_2 emissions from a biomass source of given re-growth or rotation period and the result is the equivalent amount of CO_2 that should be accounted for causing GWP. As the LCA methodology and its application continue to grow, such bioenergy studies have gained more and more credence in the policy-making spectrum (Bird *et al.*, 2011; Dandres *et al.*, 2012). Therefore, GWP_{bio} factors need to be applied in such studies to convey a more accurate measure of the climate change impact of a given bioenergy system.

Although the application of these GWP_{bio} factors is quite straight forward, the current literature only provides results for the case where all available biomass is removed. However, one of the most common practices in forestry is to harvest the stem fraction only, and leave the residues on the forest floor to decompose. In some cases, a certain percentage of forest residues are also extracted. Clearly, when residues are left, there are also significant levels of emissions from the decomposition of residual biomass that remains in the harvesting pool that gradually oxidizes as CO_2 to the atmosphere. This is inherent of all bioenergy systems. These emissions should therefore be considered when calculating the climate impacts as a consequence of bioenergy production.

Bioenergy from forestry systems is particularly important when accounting for residual CO_2 emissions. This is mainly due to two reasons. Firstly, a considerable quantity of the biomass that is available from trees is left upon the forest floor to decay via heterotrophic decomposition. Secondly, managed forests generally have relatively long rotation periods and therefore take lengthy periods to sequester the biomass that was felled. Harvesting is an anthropogenic forest disturbance that has been found to significantly influence the biogeochemical interactions between forest and the atmosphere (Fang *et al.*, 2001; Schimel *et al.*, 2001; Kauppi *et al.*, 2006; Masek & Collatz, 2006; Zhao *et al.*, 2009; Liu *et al.*, 2011). In fact, regenerating forests upon such a disturbance have been found to remain as net sources of CO_2 for at least one to two decades after logging and this is largely due to the heterotrophic decomposition of forest residues (FR) left upon the forest floor (Olsson *et al.*, 1996; Yanai *et al.*, 2003; Clark *et al.*, 2004). The time it takes for this net carbon flux to become a net sink depends on the amount of FR extracted. In this sense, a bioenergy system that manages FR with very little FR extraction will in turn have a higher climate impact potential on a unit bioenergy basis than a system that extracts nearly all of the FR that is available.

Here, we present a methodology that extends from an earlier study (Cherubini *et al.*, 2011a) to also include these residual fuel-based CO_2 emissions. We apply it to the case of Norwegian Spruce (NS) stands in Norway and we consider how the GWP_{bio} factor changes as a function of forest residue extraction efficiency. We present the remainder of the article in the following way. In the methodology section, we first give a brief description of the forest system where a more extensive explanation of the assumptions is given in the supporting information (SI) and then we explain the equations for calculating the GWP_{bio} factors. The results section follows with an illustration of the CO_2 decay and cumulative radiative forcing dynamics where the associated GWP_{bio} factors are tabularized. We then end with a discussion of certainty, implications and recommendations for applying and developing these factors.

Materials and methods

Forest system and residue decomposition

A region of Norway that is central to the forest industry (Hedmark and adjacent counties) was chosen for this forestry system analysis. The managed forest stand is assumed to be even aged and extracted in a single clear-cut after a 100-year rotation period. The same species is assumed to be immediately regrown after harvest and an equivalent amount of carbon that was clear-cut (left in forest and extracted) is assumed to be sequestered over the rotation period. NS (*Picea abies)* stands were considered in this study for their dominance in Norway and in addition to their suitability for stump/below-ground residue extraction. The normalized growth curve for NS in all scenarios was assumed to follow the Schnute function (Schnute, 1981) as was applied in Cherubini *et al.*, 2011b. Lehtonen *et al.* (2004) expansion factors were applied to determine the mass of all tree components; although these expansion factors are based on similar yet Finnish boreal forests, several Norwegian-based studies have utilized them as being applicable equations for Norwegian conditions (de Wit *et al.*, 2006; Rørstad *et al.*, 2010; Bright *et al.*, 2011). To estimate the biogenic CO_2 emissions associated to the fraction of FR that remained upon the forest floor, we used the dynamic soil carbon model Yasso07 (Tuomi *et al.*, 2008, 2009). Nine FR extraction scenarios (see Table 1) were considered where FR component specific decomposition profiles (see Fig. 1) were determined with Yasso07. (Please refer to the supporting information for further details into the FR decomposition and the NS re-growth model used).

As seen in Table 1, nine FR extraction scenarios are considered where mass percentages of each FR component were calculated using Lehtonen *et al.* (2004) expansion factors and decomposition profiles were simulated using Yasso07. Therefore, the decomposition rate of the FR composition remaining upon the forest floor is FR component specific, and the aggregate decomposition of remaining FR components is sensitive to changing the FR extraction scenario. We consider the above nine FR extraction scenarios to gain a sense of how the GWP_{bio} factor changes with varying FR removal fraction.

Table 1 FR extraction scenarios where% AGR is the percentage of above-ground residues removed and% BGR is the percentage of below-ground residues removed

FR components	1. 0% AGR/ 0% BGR	2. 25% AGR/ 0% BGR	3. 50% AGR/ 0% BGR	4. 75% AGR/ 0% BGR	5. 75% AGR*/ 0% BGR	6. 100% AGR/ 0% BGR	7. 50% AGR*/ 50% BGR	8. 75% AGR*/ 75% BGR	9. 100% AGR/ 100% BGR
Tops	0%	25%	50%	75%	75%	100%	50%	75%	100%
Live branches	0%	25%	50%	75%	75%	100%	50%	75%	100%
Dead branches	0%	25%	50%	75%	75%	100%	50%	75%	100%
Foliage	0%	25%	50%	75%	25%	100%	25%	25%	100%
Stumps	0%	0%	0%	0%	0%	0%	50%	75%	100%
Coarse roots	0%	0%	0%	0%	0%	0%	50%	75%	100%
Small roots	0%	0%	0%	0%	0%	0%	25%	38%	100%
Fine roots	0%	0%	0%	0%	0%	0%	0%	0%	100%
Above-ground FR	0%	25%	50%	75%	59%	100%	42%	63%	100%
Below-ground FR	0%	0%	0%	0%	0%	0%	50%	75%	100%
Total FR (ω)	0%	15%	31%	46%	37%	61%	45%	65%	100%

*environmental guideline of 25% foliage extraction.

Radiative forcing

Cherubini *et al.* (2012) derived the following equation to estimate the atmospheric decay of a unit of CO_2 emissions distributed over time and with subsequent re-growth that immediately follows.

$$f(t)_i = \int_0^t e(t')_i y(t-t')dt' - \int_0^t g(t')_i y(t-t')dt'. \qquad (1)$$

Here, *f(t)* is the change in atmospheric CO_2 concentration caused by the biogenic CO_2 fluxes of the biomass system under study, where *e(t′)* is the unit of biogenic CO_2 emissions distributed over time, *y(t)* is the impulse response function (IRF) for CO_2 in the atmosphere as defined by the Bern 2.5CC model (Forster *et al.*, 2007), and *g(t)* is the normalized growth rate of the sustainably grown biomass. *e(t′)* is the function representing the emission from biomass combustion and in this case, we simulate it through a delta function (i.e. a single pulse).

Equation (1) was defined for the complete removal of all the available biomass in the resource pool. For consideration of the dynamics related to removing or leaving FR, some modifications are necessary, especially in the second term, *g(t)*, which must contain the oxidation rate of the FR left to decompose.

$$f(t) = y(t) - \int_0^t \kappa_a[g(t') - \kappa_b FR(t')]y(t-t')dt' \qquad (2)$$

The first term *y(t)* is obtained by assuming that the biogenic CO_2 emission occurs as a single pulse (see Cherubini *et al.*, 2011a), and *FR(t′)* is the curve describing the unit oxidation rate of the residues left in the forest. The resulting net in-forest carbon flux is then normalized by multiplying it by the factor κ_a. The κ_a and κ_b coefficients are defined as follows:

$$\kappa_a = \frac{1}{1-\kappa_b} \text{ where, } \kappa_b = (1-\omega)\phi \qquad (3)$$

where ω is the FR extraction efficiency or total carbon mass of forest residues extracted divided by the total carbon mass of forest residues available in the resource pool. The ϕ factor represents the fraction of total carbon biomass available (stems and FR) that is considered to be FR. On the basis of the expansion factors (Lehtonen *et al.*, 2004), we used a value of 0.47 where a sensitivity analysis around this parameter can be found in the SI. The scaling coefficient κ_b therefore represents the normalized mass of residues left to decompose according to the decay rate *FR(t′)*.

Figure. 1 shows the normalized growth rate, *g(t′)*, and the normalized FR decomposition rates, *FR(t′)*, over a 100-year time span for each of the nine FR extraction scenarios. There is a slight variation in FR decomposition rate between the different FR extraction scenarios. The reason for this difference is due to the changing proportions of FR components in each extraction scenario (i.e. foliage, branches, tops, stumps and roots) that remain upon the forest floor after harvest. The *FR(t′)* profile for each specific FR extraction scenario was then used in Eqn (2).

An implication of using Eqn (2) to represent the atmospheric decay of biogenic CO_2 from an energy system is that both stem

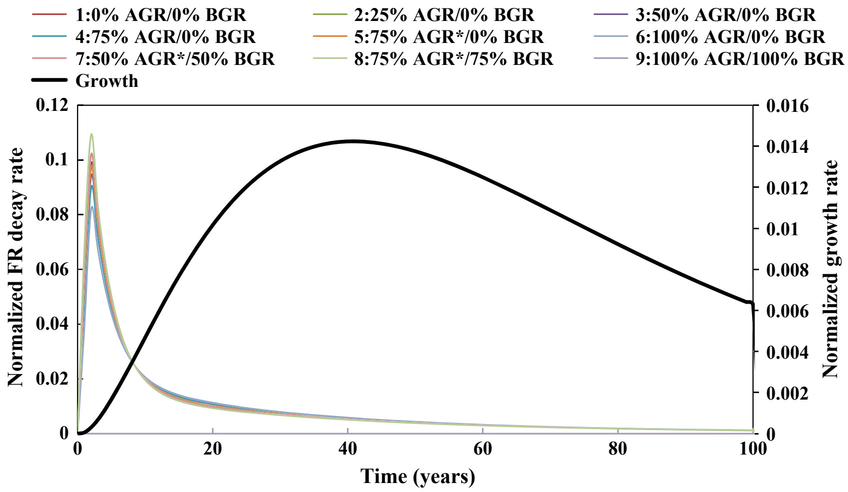

Fig. 1 The normalized growth rate, *g(t')*, and the normalized FR decomposition curves corresponding to the different FR extraction scenarios, FR *(t')*, considered in this study (*: environmental guideline of 25% foliage extraction).

and FR utilized for bioenergy will have the equivalent decay profile, and therefore, the same associated cumulative radiative forcing (CRF).

Aligning with current LCA methodology, the GWP metric was used to calculate the GWP_{bio} factor.

$$GWP_{bio} = \frac{AGWP_{bioCO_2}}{AGWP_{CO_2}} = \frac{C_0 \int_0^{TH} \alpha_{CO_2} f(t) dt}{C_0 \int_0^{TH} \alpha_{CO_2} y(t) dt} \quad (4)$$

Here, the absolute global warming potential (*AGWP*), or CRF potential, of a given pulse of biogenic CO_2 due to bioenergy production is divided by the *AGWP* of an equivalent pulse of fossil CO_2. C_o is considered to be the magnitude of the emission pulse (kg CO_2 for example) and α_{CO_2} is the radiative forcing efficiency of CO_2 [1.81E-15 W m^{-2} kg^{-1} CO_2 (Forster *et al.*, 2007)]. The resulting fraction, or GWP_{bio} factor, is the portion of biogenic CO_2 emissions that should be attributed to causing climate change in which the resulting value is equivalent to the same amount of fossil-based CO_2 emissions. Eqn (2) can be inserted into Eqn (4) to calculate the GWP_{bio} factors for the different cases of forest residues removal rates, ω. If ω is equal to one, or 100% of the FR is extracted, then Eqn (2) will simplify back to Eqn (1). The variables used in the equations are summarized in Table 2.

Results

In Fig. 2a, the atmospheric CO_2 decay curves of the nine FR of extraction scenarios are presented along with the decay of CO_2 from fossil fuel combustion. The nine scenarios were chosen for their extreme cases and their likeliness of occurring in industry. The initially high rate of FR decomposition leads to a more gradual decay of the normalized biogenic CO_2 pulse from the atmosphere. As a consequence, more radiative forcing accumulates when a higher fraction of the FR is left upon the forest floor as can be seen in Fig. 2b.

This is sensible since additional CO_2 emissions from the forest are attributed to the unit CO_2 pulse emission and the bioenergy conversion site. In fact, as seen in Fig. 2b, several of the unit biogenic CO_2 pulse scenarios create more CRF than the unit fossil CO_2 pulse in the short-term. However, since an equivalent amount of the biogenic CO_2 being emitted is sequestered by the sustainable re-growth of the biomass, the CRF of all unit biogenic CO_2 pulse scenarios soon becomes less than that of the unit fossil CO_2 pulse.

The GWP_{bio} is the ratio of the area under the CRF curve of the given FR extraction scenario divided by the area under the CRF curve due to a unit pulse of CO_2 from a fossil source at a given point in time (see (Cherubini *et al.*, 2011a) for more details). In Table 3, the GWP_{bio} factors tell us the cumulative climate impact potential of a unit pulse of biogenic CO_2 at conversion plant relative to a unit pulse of fossil CO_2 over a given TH. According to Eqn (2), the climate impact due to the unit CO_2 pulse emission for bioenergy directly refers to the biomass combusted, and would be equally applied when either stems or forest residues are burnt. The bioenergy CO_2 emission pulse could be any combination of stem wood and FR wood. All combinations will result in the same GWP_{bio} factors as long as the FR extraction efficiency is assumed to be the same. The resulting value will be the CO_2 equivalents (CO_{2eq}) that should be accounted towards contributing to *GWP* over a given TH.

For a TH of 20 years, results indicate that most FR extraction scenarios lead to the unit biogenic CO_2 pulse

Table 2 List of symbols used in the equations with definitions and dimensions

Symbol	Definition	Dimensions
GWPbio	Biogenic CO_2 GWP characterization factor	kg $CO_{2eq.}$ per kg biogenic CO_2 emissions
$f(t)$	Biogenic CO_2 decay profile	Normalized to one
$e(t)$	Distributed biogenic CO_2 emission profile	Normalized to one
$y(t)$	Fossil CO_2 decay profile	Normalized to one
$g(t)$	Re-growth rate of biomass system	Normalized to one
$FR(t)$	Decomposition profile of FR left in forest	Normalized to one
κ_a	Total biomass clear-cut normalized to a unit biomass extracted	Unitless: kg biomass felled/re-grown per kg biomass extracted
κ_b	Fraction of FR left in forest normalized to total biomass available	Unitless: kg FR left per kg biomass available
ω	FR extraction efficiency	Unitless: kg FR extracted per kg FR available
ϕ	Fraction of biomass that is in the form of FR	Unitless: kg FR per (kg FR + kg stem wood available)

creating more *GWP* than a unit CO_2 fossil pulse. This is for all cases where the GWP_{bio} factor is larger than one. As the TH increases, the unit biogenic CO_2 pulse scenarios become significantly better than the fossil CO_2 pulse. For example, removal of 75% AGR and 0% of BGR would lead to 51% of the *GWP* created by an equivalent emission pulse of fossil CO_2 when a TH of 100 years is applied.

However, there is a large variance between the FR extraction scenarios. In the two extreme cases—0% FR extracted ($GWP_{bio,TH=100} = 0.62$) and 100% FR extracted ($GWP_{bio,TH=100}$ = 0.44)—around 18 more percentage points of CO_2 emissions from the bioenergy conversion site should be accounted for contributing to climate change if a TH of 100 years is considered. In this sense, a greater level of climate change mitigation can be achieved the more FR is extracted from the forest floor. When the GWP_{bio} factors are calculated at a TH of 500 years, the variance between the FR extraction scenarios significantly dampens and very little variance in the GWP_{bio} factors is found across the FR extraction scenarios as can be seen in Table 3.

Discussion

Bioenergy systems that rely on biomass with long-rotational re-growth periods have been found to significantly impact the climate even when carbon-flux neutral biogenic-sourced CO_2 emissions are assumed (Cherubini *et al.*, 2011a). This work has shown that CO_2 emissions from biomass inherent of the bioenergy system that is left to decompose within the biomass resource pool is also an important emission source to consider. Depending on the fraction of available FR that is extracted, these residual CO_2 emissions in the forest can significantly increase the GWP_{bio} factor that should be used for a given bioenergy system. An equivalent amount of all CO_2 being emitted in the presented cases was assumed to grow back sustainably and therefore no direct (Fargione *et al.*, 2008) or indirect (Searchinger, 2010) land-use change was accounted for; however, these two issues may be important considerations in a given LCA study for which the GWP_{bio} methodology (Cherubini *et al.*, 2011a) could be applied.

Some LCA literature has suggested that the climate impacts due to FR should be disregarded because FR is viewed as a waste stream that would otherwise be left to decompose if it were not utilized for bioenergy (Higo & Dowaki, 2010; Kravanja *et al.*, 2012; Pa *et al.*, 2012). However, this work takes on the viewpoint that FR is a forest co-product (McKechnie *et al.*, 2010; Whittaker *et al.*, 2011). If the rotation period and FR extraction efficiency is the same for the harvested stem and FR, then the given GWP_{bio} factors will be equivalent regardless of whether the energy plant is combusting AGR, BGR, stem wood or in any combination thereof. Also, although one could alternatively disaggregate the CO_2 pulse emission at the energy plant and the distributed CO_2 emission profile upon the forest floor, and treat these emissions as separate inventory items, the ease of applying a single GWP_{bio} factor that covers both emission sources will clearly streamline accounting procedures.

Procurement losses are also significant in certain bioenergy systems (Forsberg, 2000) and such emissions could technically be incorporated into the GWP_{bio} factor while maintaining its normalization to a unit CO_2 pulse at the energy conversion site. However, from an LCA perspective, we think it is more sensible to treat the procurement losses as a separate process or inventory item in the value chain while applying a GWP_{bio} factor that does not change as a function of procurement loss.

The GWP_{bio} factor can then be seen as a straight forward metric that can be used from either an attributional or a consequential perspective. They are fully consistent with the GWP factors as defined by the IPCC and that are commonly applied in LCA.

However, such characterization factors are simplistic in terms of assuming climate conditions similar to

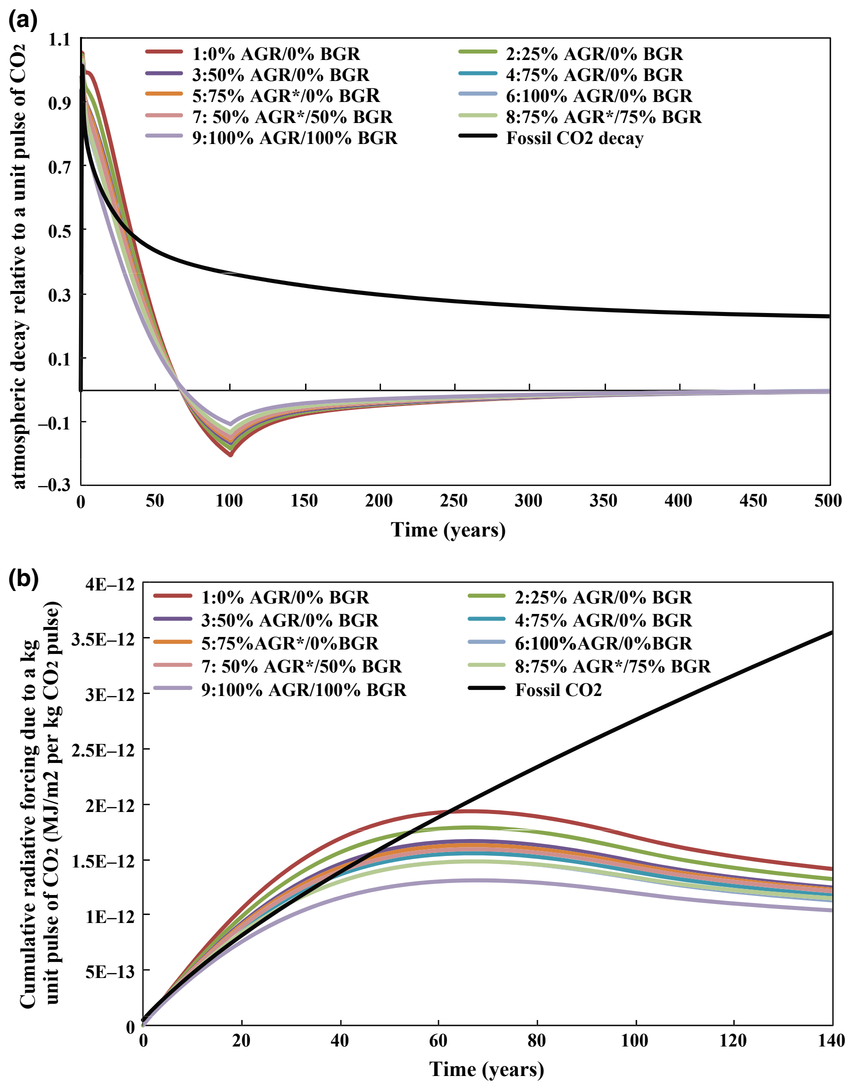

Fig. 2 (a) Atmospheric CO_2 decay profiles due to a unit CO_2 pulse of bioenergy at conversion site with consideration of CO_2 emissions due to decomposition of the fraction of forest residues that remain upon the forest floor. (b) Associated cumulative radiative forcing. The nine FR extraction scenarios are considered, along with a unit fossil CO_2 emission pulse. (*: environmental guideline of 25% foliage extraction).

recent history simulated over a 500 year span along with a constant background atmospheric CO_2 concentration of 378 ppm (Forster *et al.*, 2007). As atmospheric CO_2 concentration increases, changes in biomass growth rate, regional temperature and precipitation are likely to increase in the boreal region (Kellomäki *et al.*, 2008). This would also likely increase the marginal atmospheric decay rate of CO_2 and yet decrease the marginal radiative efficiency of CO_2 (Sathre & Gustavsson, 2011). Therefore, the climatic changes due to increasing atmospheric CO_2 concentrations and other climate perturbations in the atmosphere that may occur in the future are not accounted for. If this were taken into account, then FR decomposition rates would likely increase slightly. This may also change the resulting atmospheric decay curve or IRF of a fossil CO_2 pulse. The GWP_{bio} factors are not foreseen to change significantly in terms of changing IRF since both the numerator and denominator are a function of the same IRF.

The level of FR extraction may alter the forest re-growth profile. Although FR removal has been found to reduce subsequent forest growth (Zabowski *et al.*, 1994; Helmisaari *et al.*, 2011), FR removal can also assist with efficient planting of seedlings (Veli-Matti, 2006) and fertilizer compensation has been found to have significant net climate cooling benefits (Eriksson *et al.*, 2007; Sathre *et al.*, 2010). Due to the lack of empirical research on these tradeoffs, we maintained the same re-growth profile for all FR extraction scenarios. Forest soil disruption associated with above-ground FR and stump/coarse

Table 3 GWP_{bio} characterization factors for 20-, 100- and 500- year time horizons for each of the nine FR extraction scenarios considered.

Scenario	20-year TH	100-year TH	500-year TH
0% AGR/0% BGR	1.30	0.62	0.09
25% AGR/0% BGR	1.22	0.58	0.09
50% AGR/0% BGR	1.15	0.54	0.09
75% AGR/0% BGR	1.09	0.51	0.08
75% AGR*/0% BGR	1.13	0.53	0.09
100% AGR/0% BGR	1.05	0.49	0.08
50% AGR/50% BGR	1.11	0.52	0.09
75% AGR/75% BGR	1.06	0.49	0.08
100% AGR/100% BGR	0.96	0.44	0.08

*environmental guideline of 25% foliage extraction.

root removal may lead to soil carbon permanently lost to the atmosphere. Unfortunately, empirical research on the magnitude of these emissions is few in number (Jandl *et al.*, 2007; Walmsley & Godbold, 2010). However, a simplified analysis sensitive to percentage of soil carbon disturbed that is lost permanently due to BGR extraction can be found in the SI. This sensitivity analysis suggests that relatively small permanent soil carbon losses due to BGR extraction means that maximizing FR extraction may not lead to the least radiative forcing FR extraction scenario.

The Yasso07 model has been shown to give unbiased estimates for the decomposition of woody and non-woody litter (Tuomi *et al.*, 2009). The decomposition of FR in this study was found to fit well with past work that utilized the Yasso07 model (see SI for illustrative comparison) (Repo *et al.*, 2011, 2012). Despite the uncertainties, it is our assessment that the current estimates are reliable enough to demonstrate the magnitude of radiative forcing associated with producing bioenergy from harvested biomass in boreal coniferous forests and the notable differences between the extraction scenarios. As more empirical results materialize, results can easily be updated.

The CO_2 emissions due to biomass residual decomposition within the biomass resource pool are foreseen to be of particular importance in forest bioenergy systems and quite negligible for short rotation systems like annual energy crops. Regional meteorological conditions play a key role in determining these GWP_{bio} factors because local climate conditions will have a great influence on biomass rotation period and biomass residual decomposition rate. Therefore, region and species specific growth rates and decomposition profiles should be modelled and utilized to calculate regionalized GWP_{bio} factors for a specific bioenergy system.

The 100-year time horizon has been most commonly applied in LCA studies and is thought to be the most suitable TH for making policy-related decisions. Results from Table 3 indicate that the CO_2 being emitted from long rotation NS-based bioenergy creates a significant impact on the climate. With this TH of 100 years, the CRF is in the range of 44–62% relative to a fossil CO_2 emission. This is significant, and therefore in order for NS-based bioenergy to be warranted as a sound renewable energy for climate change mitigation, it should be efficiently utilized. Simultaneously, effective policies need to be implemented to ensure efficient substitution of fossil energy systems. The carbon neutral-equals-climate neutral paradigm needs to be overcome and biogenic CO_2 emissions from sustainably grown biomass should no longer be accounted for creating 0% climate change impact potential.

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Supporting Information

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

Data S1. Further details on forest residue decomposition modeling and GWPbio factor sensitivity analysis.

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