GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2011) **3**, 413–426, doi: 10.1111/j.1757-1707.2011.01102.x

CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming

FRANCESCO CHERUBINI*, GLEN P. PETERS†, TERJE BERNTSEN†‡, ANDERS H. STRØMMAN* and EDGAR HERTWICH*

*Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway, †Center for International Climate and Environmental Research – Oslo (CICERO), Oslo, Norway, ‡Department of Geosciences, University of Oslo, Norway

Abstract

Carbon dioxide (CO_2) emissions from biomass combustion are traditionally assumed climate neutral if the bioenergy system is carbon (C) flux neutral, i.e. the CO_2 released from biofuel combustion approximately equals the amount of CO_2 sequestered in biomass. This convention, widely adopted in life cycle assessment (LCA) studies of bioenergy systems, underestimates the climate impact of bioenergy. Besides CO_2 emissions from permanent C losses, CO_2 emissions from C flux neutral systems (that is from temporary C losses) also contribute to climate change: before being captured by biomass regrowth, CO_2 molecules spend time in the atmosphere and contribute to global warming. In this paper, a method to estimate the climate impact of CO_2 emissions from biomass combustion is proposed. Our method uses CO_2 impulse response functions (IRF) from C cycle models in the elaboration of atmospheric decay functions for biomass-derived CO_2 emissions. Their contributions to global warming are then quantified with a unit-based index, the GWP_{bio}. Since this index is expressed as a function of the rotation period of the biomass, our results can be applied to CO_2 emissions from combustion of all the different biomass species, from annual row crops to slower growing boreal forest.

Keywords: bioenergy, carbon neutral, CO_2 accounting, global warming potential, LCA

Received 14 October 2010; revised version received 31 January 2011 and accepted 7 February 2011

Introduction

Background

In 1991, the first comprehensive guidelines for estimating national greenhouse gas (GHG) emissions and sinks compiled by the Organization for Economic Cooperation and Development (OECD) states that 'CO_2 emissions resulting from bioenergy consumption should not be included in a country's official emission inventory' (OECD, 1991). This convention is motivated by the consideration of the carbon (C) neutrality of bioenergy: because growing forests sequester C, then as long as areas harvested for biomass are kept forested, the C is again absorbed in growing trees and consequently the net impact on GHG emissions is zero (Manomet, 2010). For this reason, in national GHG inventories direct carbon dioxide (CO_2) emissions from bioenergy are not reported in the energy sector (as for fossils) but in the land use, land-use change and forestry (LULUCF) sector, according to country-specific regulations (UNFCCC, 2003; IPCC, 2006). Stemming from this convention, primary research life cycle assessment (LCA) studies tend to implicitly assume CO_2 emissions from biomass combustion climate neutral if the bioenergy system is C flux neutral, i.e. CO_2 emissions from temporary C losses are traditionally ignored.

In LCA studies of bioenergy systems, the OECD convention is implemented following two basic accounting procedures. The majority of case studies ignore the CO_2 flux within a bioenergy system, assuming that CO_2 absorbed equals CO_2 emitted, so giving a net flux balance of zero; these studies simply assign a global warming potential (GWP) equal to zero to direct CO_2 emissions (e.g., Carpentieri *et al.*, 2005; Petersen Raymer, 2006; Huo *et al.*, 2008; Kim & Dale, 2008). Other studies follow the EcoInvent database (Werner *et al.*, 2003) and offset CO_2 emissions from biomass combustion with an upstream sequestration credit that is nearly equal to the combustion emission. In this case, a GWP equal to 1 is assigned to CO_2, which is considered to be

Correspondence: Francesco Cherubini, tel. + 477 359 8942, e-mail: francesco.cherubini@ntnu.no

offset by the sequestration of the same amount of CO_2 that occurred to grow biomass (Reijnders & Huijbregts, 2008; Luo *et al*., 2009).

These accounting conventions are so widely adopted that in the majority of LCA studies it is not even mentioned which one of the two is used (van der Voet *et al*., 2010; Cherubini & Strømman, 2011). A recent paper reports that in only four of the 67 case studies reviewed the exclusion of the climate effect of biomass-derived CO_2 emissions is explicitly indicated, while in two cases it is clearly mentioned that emissions and removals are both included and offset (van der Voet *et al*., 2010). Most of the studies generally find a reduction in the contribution to climate change when bioenergy systems are compared to fossil reference systems, provided that permanent changes in terrestrial C pools are minimized (Quirin *et al*., 2004; Searcy & Flynn, 2008). One of the main reasons for this result is the absence in GHG balances of the climate impact of CO_2 emitted from biomass combustion.

Both in past and recent literature, an increasing perception of the inadequacy of this accounting convention and its implementation in LCA can be identified. Already some years ago, Börjesson & Gustavsson (2000) did not presume wood to be C neutral and accounted for CO_2 emissions from biomass as those from fossils. Rabl *et al*. (2007) advocated 'that emission and removal of CO_2 be accounted explicitly at each stage of the life cycle' . Even if they realized that the net effect at the end would be almost zero, they claim that using this approach allows a dynamic modeling of emissions and removals. Others have questioned the distinction between fossil and biomass-derived CO_2 in national GHG accounting, emphasizing that 'all CO_2 is equal in the atmosphere' and IPCC only provides vague guidance concerning this crucial matter, and further detailed analysis would be highly desirable to accurately account for all CO_2 fluxes (Möllersten & Grönkvist, 2007). Johnson states that we should say 'goodbye to C neutral' for bioenergy from forests (Johnson, 2009), while other researchers have focused on fixing 'a critical climate accounting error' (Searchinger *et al*., 2009; Searchinger, 2010). Searchinger *et al*. (2009) moved a step forward, stating that 'replacing fossil fuels with bioenergy does not by itself reduce C emissions', since the CO_2 released by tailpipe emissions 'is roughly the same per unit of energy': in order to mitigate climate change, bioenergy must ensure that 'the growth and harvesting of the biomass for energy captures more C above and beyond what would be sequestered anyway and thereby offset emissions from energy use'.

A further distinction can be seen between LCA based on forest wood and fast growing biomass species (annual crops and lignocellulosic energy crops). Studies which focus on bioenergy from fast growing biomass generally tend to account for permanent changes in terrestrial C pools only, while basically ignoring the climate impact of CO_2 from temporary changes (i.e. biomass harvested for bioenergy and then regrown). This is a reasonable assumption for fast growing species, but may not apply in the case of biofuels from slower growing biomass, like forests (Johnson, 2009; Marland, 2010). A forest may take up to 100 years to regrow, and the system can be defined C neutral only at the end of proper time boundaries: CO_2 is emitted in one point in time when biomass is burnt but the sequestration in the new vegetation is spread over several years, depending on the specific rotation period. Even if in these cases the fact that C neutral does not mean climate neutral is straightforward, this aspect has been seldom considered in LCA, despite the importance of the issue being thoroughly acknowledged from the early 1990s (Harmon *et al*., 1990; Marland & Schlamadinger, 1995; Schlamadinger & Marland, 1996b). Studies that considered the time dimensions of forest growth are essentially studies of forest C dynamics. These studies usually report an increase in GHG emissions of forest bioenergy systems in the short term, in favor of a decrease in net GHG emissions in the longer term; in some cases, a specific C deficit and pay-back time (up to some decades, depending on site-specific parameters and reference system) is identified (Marland & Schlamadinger, 1995; Schlamadinger & Marland, 1996b; Manomet, 2010; McKechnie *et al*., 2010). Many analytical models are available to perform this type of temporal analysis (Schlamadinger & Marland, 1996a; Masera *et al*., 2003; Schelhaas *et al*., 2004; Kurz *et al*., 2009). A common feature of these assessments is to show results as a trend of cumulative CO_2 emissions over century timescales, and do not elaborate yearly unit based indicators. The work performed in this paper bridges this type of analysis with LCA methodology, providing a methodology to estimate the contribution to global warming of CO_2 flux neutral bioenergy systems in terms of GWP, so to provide an index which can be promptly included in LCA.

Aims and objectives

All CO_2 emissions, both from combustion of fossil fuels or biomass, alter the C cycle and hence the earth's radiative balance, thus causing a climate impact that should be estimated. Our main aim in this paper is to quantify the climate impact of biomass-derived CO_2 emissions with a unit-based indicator to be used in LCA or C accounting studies. We focus on a single biomass rotation where an existing aboveground C stock, either a crop or a forest, is harvested for bioenergy and later

allowed to regrow. We use this schematic case to retain the focus on the key research question, without adding the complexity and additional assumptions linked to the possibilities of using specific factors like local conditions and biomass management strategies.

This paper is structured as follows. The current method used to estimate the atmospheric decay of anthropogenic CO_2 emissions is firstly described together with a metric for measuring their contribution to GWP. Afterwards, the climate impact of CO_2 emissions from biomass combustion (bio CO_2, from this point forward) is investigated through the formulation of proper atmospheric decay functions, which are used in the GWP_{bio} index. Finally, results are presented as a function of the biomass rotation period, and the most relevant implications related to this methodology are discussed in the final section.

Materials and methods

Anthropogenic CO_2 emissions

C cycle climate models. CO_2 emissions play a key role in the earth's C cycle and climate system. Those which are classified as anthropogenic (i.e. from fossil fuel combustion, cement production, deforestation and land-use change) are one of the main responsible for anthropogenic climate change (Forster *et al*., 2007). Complex C cycle climate (CC) models, which establish the link between atmospheric CO_2 concentration and anthropogenic C emissions by modeling uptake and exchange fluxes of the atmosphere with the oceans and the terrestrial biosphere, are used to model the time evolution of airborne CO_2. In order to make analysis easier for smaller case studies, such as LCA, impulse response functions (IRF) are often used to represent CO_2 atmospheric decay under given assumptions (Tubiello & Oppenheimer, 1995; Joos & Bruno, 1996; Enting *et al*., 2001).

The oceans play an important role for the removal of anthropogenic C. They are generally distinguished into the upper layer, which has a very fast turnover rate (Wanninkhof, 1992), and the deep ocean, to which C is transported through oceanic circulation (Joos, 2003). This latter process is the limiting factor for the ocean's uptake capacity, which is determined by ocean volume and sea water chemistry. This uptake capacity is only reached after several centuries, and it takes millennia to equilibrate ocean water and sediments after a perturbation in oceanic C content. Changes in the land biosphere and in the upper ocean influence atmospheric CO_2 concentrations on seasonal to century time scales. Several models dealing with the C cycle in the oceans have been formulated (Oeschger *et al*., 1975; Siegenthaler & Joos, 1992; Blanke & Delecluse, 1993; Caldeira & Kasting, 1993).

Modeling the terrestrial components of the C cycle is more challenging because of the natural variability of some basic parameters (Enting *et al*., 2001). The most common way of modeling terrestrial C transfers is to use discrete compartments as leaves, branches, soil C, etc., characterized by an initial C content and turnover times. The C transfers from the air to the plants is described by a net primary production, which may depend on specific parameters like temperature, nutrient levels, water supply and others. The terrestrial part of the different climate models usually differ in the number of physiological compartments, feedback effects and the degree of disaggregation (Friedlingstein *et al*., 1994, 1995; Prentice *et al*., 2000; Cramer *et al*., 2001; McGuire *et al*., 2001).

Atmospheric decay. Thanks to the elaboration of these CC models it is possible to predict the atmospheric decay of CO_2 emissions (Maier-Reimer & Hasselmann, 1987; Lashof & Ahuja, 1990; Caldeira & Kasting, 1993; Joos *et al*., 1996, 2001; Enting *et al*., 2001). In all the cases, CO_2 does not follow a simple decay according to one single lifetime (as it is for the two other main GHG, N_2O and CH_4), but its decay is described by several time constants and there is a fraction of the initial emission that always remains in the atmosphere. The fraction of CO_2 remaining in the air following a CO_2 release depends on future atmospheric CO_2 concentrations, because the partial pressure of CO_2 in the ocean surface is a nonlinear function of surface total dissolved inorganic C concentration (Caldeira & Kasting, 1993).

The analytical form of the atmospheric decay of anthropogenic CO_2 is given by a superposition of a number of exponentials of different amplitude A_i and relaxation time τ_i

$$y_{CO_2}(t) = A_0 + \sum_{i=1}^{i=n} A_i e^{(-t/\tau_i)}. \quad (1)$$

The value of this function at any time represents the fraction of the initial emission which is still found in the atmosphere, and the removed fraction corresponds to the ocean/biosphere uptake. The amplitude A_0 represents the asymptotic airborne fraction of CO_2 which remains in the atmosphere because of the equilibrium response of the ocean–atmosphere system. The amplitudes A_i may be interpreted as the relative capacity of the other sinks, which are filled up by the atmospheric input at rates characterized by the relaxation time scales τ_i. These time scales determine the redistribution of anthropogenic CO_2

emissions in the climate system and are linked to the time scales of the natural C cycle. Because of this exponential decay trend, more than half of the initial input is removed from the atmosphere within few decades after emissions through uptake by the upper ocean layer and the fast overturning reservoirs of the land biosphere. However, a certain fraction is still found in the atmosphere after 1000 years; this fraction is only very slowly reduced further by ocean–sediment interaction and the weathering cycle (Archer *et al*., 1998).

Metrics for climate change

The climate impact of GHG emissions needs to be compared with a consistent metric. In this paper the GWP is used, rather than other possible metrics (Fuglestvedt *et al*., 2003; Shine *et al*., 2005). This metric was developed as a relative measure of the potential effects on climate of a GHG compared with CO_2. GWP heavily relies on the concept of radiative forcing which gives the perturbation of the earth energy balance at the top of the atmosphere by a climate change mechanism. The cumulative radiative forcing for a pulse emission, which is often referred to as the absolute global warming potential (AGWP), is given by the integral over time of the product between the radiative efficiency of the gas (α) and the decay function, $y(t)$, that defines the fraction of the gas remaining in the atmosphere after a unit pulse (C_0)

$$\mathrm{AGWP} = \mathrm{C}_0 \int_0^{\infty} \alpha y(t)\mathrm{d}t, \qquad (2)$$

where the radiative efficiency (α) of CO_2 is (Forster *et al*., 2007)

$$\alpha_{\mathrm{CO}_2} = 5.35 \ln\left(\frac{\left[\mathrm{CO}_2^*\right]}{\left[\mathrm{CO}_2\right]}\right). \qquad (3)$$

Where $[CO_2^*]$ is the concentration in the atmosphere after small perturbation and $[CO_2]$ is the initial concentration of CO_2 in the atmosphere. If the background concentration of 378 ppm provided by the IPCC report is used, and a perturbation of 1 ppm is applied, the value of the radiative efficiency for CO_2 is 1.41×10^{-5} $\mathrm{W\,m^{-2}\,ppb^{-1}}$.

Since the decay of a CO_2 pulse emission has a non-zero asymptote, its integral from zero to infinity is infinite. To avoid this, several attempts to define an effective residence time for CO_2 in the air have been formulated (Houghton *et al*., 1990; Lashof & Ahuja, 1990; Rodhe, 1990; Moore & Braswell, 1994). In the 1990s, the IPCC introduced finite time horizons (THs) (20, 100 and 500 years) for integration in the GWP, where the CO_2 decay function by Joos *et al*. (1996) was used (Schimel *et al*., 1996). As specified by the IPCC itself, these different THs should not be considered of any scientific significance (Fuglestvedt *et al*., 2003; Forster *et al*., 2007). GWPs were then elaborated for all the different GHGs (denoted as *i*) according to this equation

$$\mathrm{GWP}_i = \frac{\mathrm{AGWP}_i}{\mathrm{AGWP}_{\mathrm{CO}_2}} = \frac{C_0 \int_0^{\mathrm{TH}} \alpha_i y_i(t)\mathrm{d}t}{C_0 \int_0^{\mathrm{TH}} \alpha_{\mathrm{CO}_2} y_{\mathrm{CO}_2}(t)\mathrm{d}t}. \qquad (4)$$

GWP then acts as a metric able to aggregate emission of the various gases to a common unit (kg CO_2-eq.). In Table 1, GWPs for given THs are shown for the three most important GHGs, together with their lifetime and radiative efficiency.

CO_2 emissions from biomass combustion

The atmospheric decay of CO_2 emissions from biomass combustion can be predicted with the IRF from C climate models only if biomass is not replanted (i.e. deforestation), or a LUC occurs. Even if consistent results were achieved in upgrading the modeling of the biosphere compartment (Gerber *et al*., 2004), the basic principles remain unchanged: if biomass is replanted, emissions from combustion are neutralized by CO_2 removal during regrowth; if biomass is not replanted, bio CO_2 emissions become anthropogenic CO_2 (Strassmann *et al*., 2008). Then, a new IRF needs to be elaborated to predict the atmospheric decay of bio CO_2.

Modeling assumptions. The method developed in this paper is applied to a well-defined schematic case study that is suitable to demonstrate the approach

Table 1 Lifetime, radiative efficiency, and global warming potentials (GWPs) for different time horizons of the three most important greenhouse gases (GHGs)

GHG	Lifetime (years)	Radiative efficiency ($\mathrm{W\,m^{-2}\,ppb^{-1}}$)	GWP 20 years	GWP 100 years	GWP 500 years
Carbon dioxide (CO_2)	na	1.4×10^{-5}	1	1	1
Methane (CH_4)	12	3.7×10^{-4}	72	25	7.6
Nitrous oxide (N_2O)	114	3.03×10^{-3}	289	298	153

na, not available.

proposed (see Fig. 1). It is assumed that all biomass is burnt in one time step so that the CO_2 emission is modeled as a pulse. The biomass harvested is from an even-aged vegetation stand (representing the starting condition) which is clear cut and the land is immediately revegetated with the same biomass species after harvesting. We assume that the regrowth, at the end of the rotation period, captures the same amount of CO_2 that was released by combustion (i.e., we assume the entire process is C flux neutral). Only one rotation is assumed. CO_2 emissions from loss of C pools other than aboveground vegetation, like soil and litter, are not considered at this stage.

According to the most common practice in biomass growth modeling (Swallow *et al.*, 1990; Rossi *et al.*, 2009), the rate of biomass growth (or regrowth, in our case) can be modeled as a normal distribution (Gaussian), expressed as atmospheric C uptake in vegetation as a function of the rotation period of the biomass. This is a probability density function that has the following analytical form:

$$g(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(t-\mu)^2/2\sigma^2}, \quad (5)$$

where the parameters μ and σ (mean and variance) can be used to represent characteristics of forest growth. It is assumed that the mean occurs in the year with the maximum C uptake and is taken as half of the rotation period ($\mu = r/2$). The variance determines the width of the distribution, and it is here assumed to be equal to half mean ($\sigma = \mu/2$).

Calculation procedures. The concentration in the atmosphere of bio CO_2 over time can be described by means of an IRF which refers to the reaction (as a function of time) of any dynamic system in response to some external change. In our case, this means that the atmospheric decay of bio CO_2 is derived through combination of the biomass regrowth sink (the Gaussian curve, modeled as a negative emission) with the IRF modeling the removal of CO_2 by the ocean and/or terrestrial biosphere sinks. In mathematical terms, this is a convolution between two functions, based on a conventional and widely used approach (Siegenthaler & Oeschger, 1978). Then, the atmospheric CO_2 concentration $f(t)$ after a pulse emission can be represented as the sum of earlier emissions g at time t' multiplied by the fraction still remaining in the atmosphere after time $t-t'$

$$f(t) = \int_0^t [C_0\delta(t') - g(t')]y(t-t')\mathrm{d}t', \quad (6)$$

where C_0 is the pulse emission of bio CO_2 to the atmosphere, $\delta(t')$ is the delta function (which is zero everywhere except at the origin) $g(t')$ is the rate of biomass regrowth which removes the CO_2 originally released, and $y(t)$ is the IRF from the C cycle climate model. Equation (6) can be written as follows:

$$f(t) = \int_0^t C_0\delta(t')y(t-t')\mathrm{d}t' - \int_0^t g(t')y(t-t')\mathrm{d}t'. \quad (7)$$

Since $C_0 = 1$, we can write

$$f(t) = y(t) - \int_0^t g(t')y(t-t')\mathrm{d}t'. \quad (8)$$

This equation describes the atmospheric decay of a pulse of bio CO_2 over time. The term representing the biomass regrowth, $g(t')$, is defined in Eqn (5), while three alternative options are possible for the IRF $y(t)$:

1. Following the OECD convention, bio CO_2 emissions are removed from the atmosphere by the onsite biomass growth. If this closed perspective is adopted, bio CO_2 will decay from the air only because of the biomass regrowth. This means that there are no contributions from the rest of the C cycle components, and $y(t) = 1$. Since it is totally unphysical to neglect any CO_2 uptake from the oceans or other sinks, this option is considered here only to analytically demonstrate the inadequacy of the OECD convention through the inconsistent results obtained. This approach will be referred to as the vegetation IRF (VIRF).
2. As we have mentioned previously, oceans play a key role in the removal of CO_2 from the atmosphere. In this second case, the ocean sink is added to the

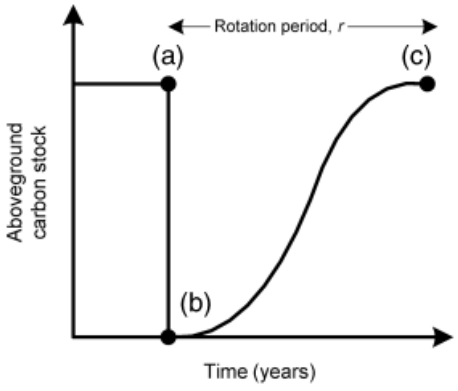

Fig. 1 Simplified scheme of the carbon flux neutral system modeled in this paper. (a) Biomass stand at steady state; (b) all aboveground carbon is harvested and emitted to the atmosphere as CO_2. Simultaneously, the same biomass is replanted and starts growing by sequestering the CO_2 released from combustion; (c) the same quantity of carbon originally released is sequestered once again in the vegetation at the end of the rotation.

vegetation regrowth sink by considering a proper climate model, so giving a specific profile for the atmospheric decay of bio CO_2, the ocean and vegetation IRF (OVIRF).

3. As considered in CC models, when a CO_2 molecule is released to the atmosphere can be removed by both the ocean and terrestrial biosphere. In this case, a complete IRF is used and the resulting atmospheric decay is referred to as the full IRF (FIRF).

In all the cases, the resulting function $f(t)$ is used in Eqn (4) to get an index of the relative climate impact of CO_2 emissions from biomass combustion

$$GWP_{bio} = \frac{AGWP_{bio\,CO_2}}{AGWP_{CO_2}} = \frac{C_0 \int_0^{TH} \alpha_{CO_2} f(t)dt}{C_0 \int_0^{TH} \alpha_{CO_2} y(t)dt}. \quad (9)$$

VIRF. In this case, the biomass C cycle is independently modeled as a closed system, from combustion to removal by vegetation regrowth, which is the only sink considered. This option appears consistent with the convention currently used in bioenergy LCA, where CO_2 emissions from biomass combustion are assumed to be offset by biomass growth.

In mathematical terms, this means that $y(t) = 1$, and Eqn (8) can be written as

$$f(t) = 1 - \int_0^t g(t')dt'. \quad (10)$$

The integral of this function is the cumulative density function, which is the total C accumulated in the biomass stand along the full rotation. This integral can be expressed in terms of the error function *erf*, so that Eqn (10) becomes

$$f(t) = 1 - \frac{1}{2}\left[1 + erf\left(\frac{t-\mu}{\sigma\sqrt{2}}\right)\right], \quad erf(t) = \frac{2}{\sqrt{\pi}}\int_0^t e^{-x^2}dx. \quad (11)$$

This allows the calculation of the atmospheric decay for CO_2 emissions from combustion of different biomass species, according to the rotation period r.

OVIRF. This case models the removal of bio CO_2 from the atmosphere because of two compartments, the oceans and the vegetation sink due to biomass regrowth. The rest of the terrestrial biosphere is not considered here as a possible sink. The same approach has been considered in the past to predict the contribution to climate change of CO_2 emissions from a forest fire (Randerson *et al*., 2006). As in the VIRF case, the vegetation sink is modeled with the Gaussian distribution, while a proper CC model is to be used to predict the atmospheric decay due to ocean uptake. The IRF of scenario #4 from the ocean model described in Caldeira & Kasting (1993) is selected. This is a box-diffusion ocean model appropriate only on time scales lower than 1000 years, when interaction with sediments and rock cycles is of secondary importance. In this case, atmospheric CO_2 content is stabilized at 550 ppm by year 2150, the 1990 growth rate in atmospheric CO_2 content is 1.66 ppm yr^{-1} and the growth rate at the stabilization date is zero. The IRF resulting from this ocean model has the analytical form of Eqn (1), whose parameters are reported in Table 2 and profile is shown in Fig. 2.

If Eqn (1) is included in Eqn (8), we have

$$f(t) = A_0 + \sum_{i=1}^{i=4} A_i e^{-t/\tau_i} - \int_0^t \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(t'-r/2)^2/2(r/4)^2} \left(A_0 + \sum_{i=1}^{i=4} A_i e^{-t-t'/\tau_i}\right) dt' \quad (12)$$

The integral is estimated by numerical approximation.

FIRF. CO_2 emissions from biomass combustion are here considered to be removed from all the possible sinks, the oceans, the terrestrial biosphere and the onsite biomass regrowth. This integrates bio CO_2 emissions into the global C cycle. A complete IRF should be therefore used. Among the existing models, the IPCC Fourth Assessment Report selected the IRF derived from an updated version of the Bern 2.5CC model (Forster *et al*., 2007). In this paper, the same IRF is considered. A detailed description of this model can be found elsewhere (Joos *et al*., 1996, 2001). The analytic form of this IRF has been shown in Eqn (1), while its

Table 2 Parameters to be used in Eqns (1) (Bern CC model IRF) and (12) (ocean only IRF)

Parameters	Ocean only IRF	Bern 2.5CC model IRF
A_0	0.297	0.217
A_1	0.321	0.259
A_2	0.266	0.338
A_3	0.083	0.186
A_4	0.033	
τ_1	335.8	172.9
τ_2	18.4	18.51
τ_3	2.8	1.186
τ_4	0.8	

IRF, impulse response function.

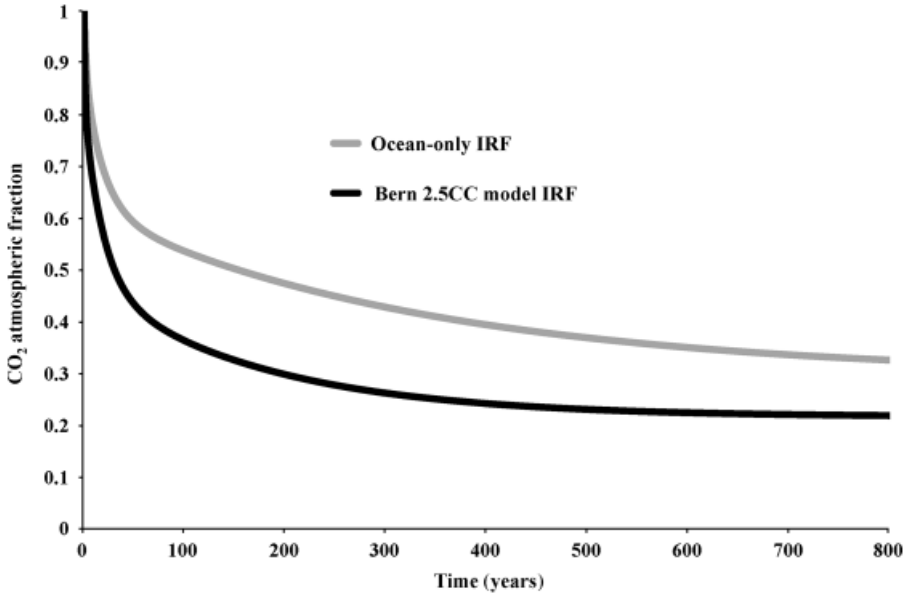

Fig. 2 Atmospheric decay of a pulse CO_2 emission according to the two different complex carbon cycle climate (CC) models considered.

parameters are reported in Table 2 and the curve is shown in Fig. 2. The profile of this function should not be directly compared with that of the ocean-only IRF presented in the previous section, because they are based on different conditions and parameters (even though a slowest decay is predictable when oceans are the only sink).

In this case, Eqn (8) can be explicitly written as follows:

$$f(t) = \left(A_0 + \sum_{i=1}^{i=3} A_i e^{-t/\tau_i}\right) - \int_0^t \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(t'-r/2)^2/2(r/4)^2} \left(A_0 + \sum_{i=1}^{i=3} A_i e^{-t-t'/\tau_i}\right) dt'. \quad (13)$$

The integral is estimated by numerical approximation. The inclusion of the terrestrial biosphere component among the sinks allows the uptake in the natural biosphere, but will potentially include a (small) form of double counting of the vegetation compartment, since also the onsite vegetation regrowth is considered. However, this should not be the case because the Bern 2.5CC model only considers the potential CO_2 uptake from stimulation of plant growth by elevated atmospheric CO_2 levels and enhanced nutrient supply, and 'does not include formulation for forestry management nor bioenergy production' (Strassmann *et al*., 2008).

Results and discussion

Bio CO_2 atmospheric decay

In Fig. 3, the three different IRF describing the decay of bio CO_2 emissions from the atmosphere are compared for selected rotation periods of 1, 10, 20, 50 and 100 years, as well as when $r \to \infty$ (that is trees are not replanted). The decay of anthropogenic CO_2 according to the Bern 2.5CC model is also shown for comparison. This decay applies in case of deforestation or permanent terrestrial C losses.

For VIRF, OVIRF and FIRF, the longer the biomass rotation period, the longer is the mean stay of CO_2 in the atmosphere. The effect of the rotation length on the FIRF-based decay is shown in Fig. 4, where the bio CO_2 fraction remaining in the air after a pulse emission is reported as a function of time and biomass rotation period. In the long term, all the decays asymptotically tend to zero, since a C flux neutral system is modeled.

As already mentioned, the VIRF curve is based on the OECD convention of a closed cycle for biomass-derived CO_2 (from combustion to uptake in new trees). Therefore, the resulting atmospheric decay simply represents the inverse (from an atmospheric point view) of the sigmoid cumulative C accumulation curve describing biomass regrowth. This is clearly inconsistent with CC models: if trees are not replanted bio CO_2 would never decay, as shown in Fig. 4 (VIRF) with $r \to \infty$. Such a result is obviously a paradox, and can be seen as an

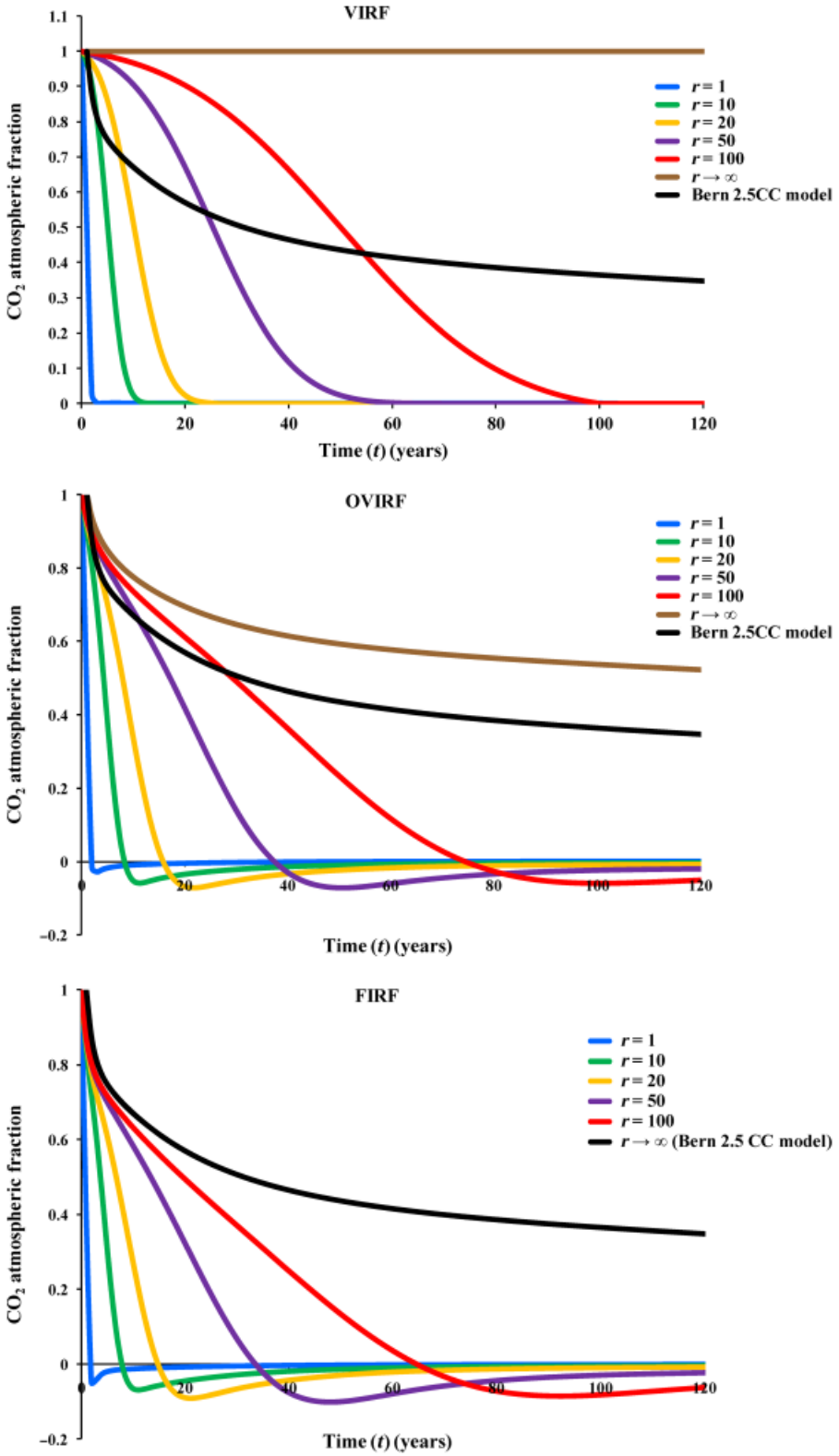

Fig. 3 CO_2 atmospheric decay following the VIRF, OVIRF and FIRF method for selected rotation periods (*r*, years). VIRF, vegetation impulse response function; OVIRF, ocean and vegetation impulse response function; FIRF, full impulse response function.

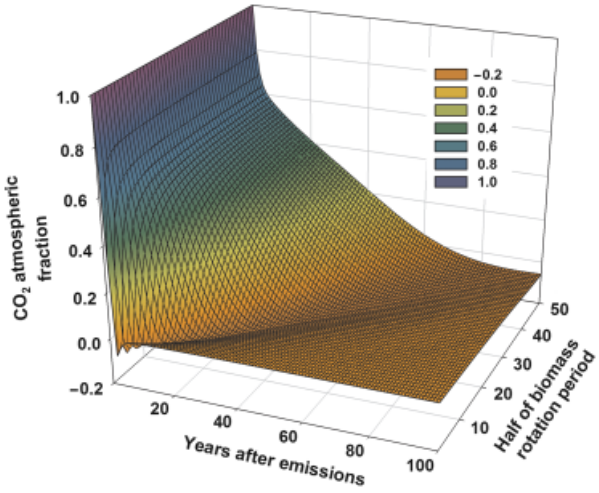

Fig. 4 Bio CO_2 atmospheric fraction as a function of time and biomass rotation period for the FIRF case. FIRF, full impulse response function.

analytical-derived evidence of the physical inaccuracy of the OECD convention.

The profile of the curves from OVIRF and FIRF are similar, since they are both the outcome of a convolution operation between the Gaussian and an exponential function. As it would have been expected, the OVIRF decay is slightly longer than the FIRF, where the CO_2 sequestration is favored by the inclusion of the terrestrial biosphere sink. This can be appreciated by looking at the points where the curves turn to negative values: for $r = 100$ years, the OVIRF becomes negative at $t \geq 71$ years, while the FIRF at $t \geq 65$ years. When $r \to \infty$, the curves are equal to the respective function $y(t)$ derived from the CC model considered in Eqns (12) and (13), for the OVIRF and FIRF case, respectively. Among the three methods, the FIRF appears as the most physically and logically consistent, and the curve for $r \to \infty$ coincides with the anthropogenic CO_2 decay.

At first sight, the presence of negative values in the atmospheric decay profiles of OVIRF and FIRF may appear as a contradiction, because the amount of CO_2 in the atmosphere is lower than the level before the emission. The reason for this is that atmospheric CO_2 is taken up in different biogeochemical sinks at different time constants, as mathematically represented by Eqn (1); as implicitly assumed by Eqn (8), the same time constants are also applied to CO_2 uptake in biomass regrowth. Soon after the emission, when the biomass growth rate is still slow, a significant fraction of the CO_2 originally released is quickly stored in the ocean upper layer. The following transport of this C to the deep ocean layers is slower, and when the uptake by the onsite biomass regrowth increases, the C initially stored in the ocean upper layer will be released back to the atmosphere at a low rate to compensate the initial overabsorption (out-gassing). In the long term, the airborne fraction of bio CO_2 approaches zero.

The GWP_{bio} index and its interpretation

The curves of Fig. 3 are used to get the climate effect of CO_2 emissions from biomass combustion after their inclusion in Eqn (9). This is a metric relative to the climate effect of anthropogenic CO_2 and based on the integration up to a defined TH. In Table 3, the GWP_{bio} index is reported as a function of the biomass rotation period for the VIRF, OVIRF and FIRF. These results are shown for the three most common THs (20, 100 and 500 years). The use of this index is identical to the other GWP equivalency factors: it is to be multiplied by the direct CO_2 emissions from biomass combustion to get their relative contribution to global warming in terms of kg CO_2-eq. This allows an estimate of the climate impact of CO_2 flux neutral systems in LCA and other similar methodologies. Results are intended to be generally applied to all biomass sources (specified with the rotation period) from annual row crops to fast growing biomass, tropical, temperate and boreal forests. For annual crops and for short rotation species, the rotation period is usually very short, from 1 to 5 years. The resulting GWP_{bio} is small, since the average lifetime of bio CO_2 in the atmosphere in this case is so short that the contribution to global warming is limited. When the rotation period becomes longer, e.g. from fast growing species ($r = 5$–20) to tropical ($r = 25$–50), temperate ($r = 55$–80) and boreal ($r = 80$–100) forest, the climate impact increases accordingly. The fact that GWP_{bio} is larger for longer rotation periods should not be over interpreted: it only means that short rotation biomass (e.g. annual crops, short rotation coppice) has less climate impact than long rotation biomass (e.g. forest wood) per unit of CO_2 emitted from the combustion of the biofuel. Before deriving general conclusions, there are many other aspects to be considered like efficiency in biomass conversion processes, number of rotations, selection of proper time and spatial boundaries, land-use changes and other life cycle implications (like material and energy inputs for cultivation, harvesting, processing and transport). Land-use changes could also include factors such as changes in surface albedo (in particular at latitudes with seasonal snow cover), change in soil C content, and changes in fluxes of heat and humidity between the surface and the atmosphere. Misleading conclusions can only be avoided by accounting for all climate forcing agents, like GHG emissions, removals and, in some cases, substitutions, within a life-cycle perspective, preferably using case-

Table 3 GWP_{Bio} index calculated with the three different methods and for three different time horizons: 20, 100 and 500 years

	VIRF			OVIRF			FIRF		
	GWP_{bio}	GWP_{bio}	GWP_{bio}	GWP_{bio}	GWP_{bio}	GWP_{bio}	GWP_{bio}	GWP_{bio}	GWP_{bio}
Rotation *r* (years)	TH = 20	TH = 100	TH = 500	TH = 20	TH = 100	TH = 500	TH = 20	TH = 100	TH = 500
1	0.04	0.01	0.00	0.03	0.00	0.00	0.02	0.00	0.00
2	0.08	0.02	0.01	0.05	0.01	0.00	0.04	0.01	0.00
4	0.15	0.04	0.01	0.11	0.02	0.01	0.09	0.02	0.00
6	0.23	0.07	0.02	0.16	0.04	0.01	0.13	0.02	0.00
8	0.30	0.09	0.03	0.21	0.05	0.01	0.18	0.03	0.01
10	0.38	0.11	0.03	0.27	0.06	0.01	0.22	0.04	0.01
12	0.45	0.13	0.04	0.32	0.07	0.01	0.27	0.05	0.01
14	0.53	0.15	0.05	0.38	0.08	0.02	0.32	0.06	0.01
16	0.60	0.17	0.05	0.44	0.09	0.02	0.37	0.06	0.01
18	0.68	0.19	0.06	0.50	0.10	0.02	0.42	0.07	0.01
20	0.75	0.22	0.07	0.55	0.12	0.02	0.47	0.08	0.02
22	0.82	0.24	0.07	0.61	0.13	0.03	0.52	0.09	0.02
24	0.89	0.26	0.08	0.66	0.14	0.03	0.56	0.10	0.02
26	0.95	0.28	0.09	0.71	0.15	0.03	0.61	0.10	0.02
28	1.00	0.30	0.09	0.76	0.16	0.03	0.65	0.11	0.02
30	1.05	0.32	0.10	0.80	0.18	0.04	0.68	0.12	0.02
32	1.09	0.34	0.10	0.83	0.19	0.04	0.71	0.13	0.02
34	1.13	0.37	0.11	0.86	0.20	0.04	0.74	0.14	0.03
36	1.16	0.39	0.12	0.89	0.21	0.04	0.76	0.15	0.03
38	1.19	0.41	0.12	0.91	0.22	0.05	0.79	0.15	0.03
40	1.21	0.43	0.13	0.93	0.24	0.05	0.80	0.16	0.03
42	1.23	0.45	0.14	0.95	0.25	0.05	0.82	0.17	0.03
44	1.25	0.47	0.14	0.97	0.26	0.05	0.83	0.18	0.03
46	1.27	0.49	0.15	0.98	0.27	0.06	0.85	0.19	0.04
48	1.28	0.52	0.16	1.00	0.28	0.06	0.86	0.20	0.04
50	1.30	0.54	0.16	1.01	0.30	0.06	0.87	0.21	0.04
52	1.31	0.56	0.17	1.02	0.31	0.06	0.88	0.21	0.04
54	1.32	0.58	0.18	1.03	0.32	0.07	0.89	0.22	0.04
56	1.33	0.60	0.18	1.03	0.33	0.07	0.89	0.23	0.04
58	1.34	0.62	0.19	1.04	0.34	0.07	0.90	0.24	0.04
60	1.35	0.64	0.20	1.05	0.36	0.07	0.90	0.25	0.05
62	1.35	0.67	0.20	1.05	0.37	0.08	0.91	0.26	0.05
64	1.36	0.69	0.21	1.06	0.38	0.08	0.91	0.27	0.05
66	1.36	0.71	0.22	1.06	0.39	0.08	0.92	0.28	0.05
68	1.37	0.73	0.22	1.07	0.41	0.08	0.92	0.29	0.05
70	1.37	0.75	0.23	1.07	0.42	0.09	0.93	0.30	0.05
72	1.38	0.77	0.24	1.08	0.43	0.09	0.93	0.30	0.06
74	1.38	0.79	0.24	1.08	0.44	0.09	0.93	0.31	0.06
76	1.39	0.82	0.25	1.08	0.46	0.09	0.94	0.32	0.06
78	1.39	0.84	0.25	1.09	0.47	0.10	0.94	0.33	0.06
80	1.39	0.86	0.26	1.09	0.48	0.10	0.94	0.34	0.06
82	1.40	0.88	0.27	1.09	0.49	0.10	0.94	0.35	0.06
84	1.40	0.90	0.27	1.09	0.51	0.10	0.95	0.36	0.06
86	1.40	0.92	0.28	1.10	0.52	0.11	0.95	0.37	0.07
88	1.40	0.94	0.29	1.10	0.53	0.11	0.95	0.38	0.07
90	1.41	0.96	0.29	1.10	0.54	0.11	0.95	0.39	0.07
92	1.41	0.98	0.30	1.10	0.55	0.11	0.95	0.39	0.07
94	1.41	0.99	0.31	1.10	0.56	0.12	0.95	0.40	0.07
96	1.41	1.01	0.31	1.10	0.58	0.12	0.96	0.41	0.07
98	1.41	1.03	0.32	1.11	0.59	0.12	0.96	0.42	0.08
100	1.42	1.05	0.33	1.11	0.60	0.12	0.96	0.43	0.08

GWP, global warming potential; VIRF, vegetation impulse response function; OVIRF, ocean and vegetation impulse response function; FIRF, full impulse response function; TH, time horizon.

specific parameters. Therefore, Table 3 does not explicitly mean that one biomass source is better than others: a lower value of the index does not necessarily reflect a lower climate impact of the whole bioenergy system.

Figure 5 shows the value of the GWP_{bio} index as a function of the biomass rotation period for the three different cases and for the three selected THs. The curves have an exponential trend to a maximum, which has the same value for each method and can be better appreciated for TH = 20 years.

The GWP_{bio} is bigger for shorter TH, because this index considers the area below the decay curve of bio CO_2 relative to that of anthropogenic CO_2. The latter has a fast decay in the first years soon after the emission and then a slow asymptotic trend towards the ocean/atmosphere equilibrium, while bio CO_2 decay tends to zero. The fact that GWP_{bio} are higher for TH = 20 years rather than for TH = 100 or 500 years confirms that bioenergy is a climate change mitigation strategy particularly effective for long-term targets.

The VIRF-based GWP_{bio} is larger than one for some circumstances. This is a direct consequence of the OECD convention on which the VIRF decay is based: the exclusion of the ocean and terrestrial biosphere uptake other than the onsite regrowth can make the climate impact of bio CO_2 approximately 1.5 times higher than that of anthropogenic CO_2. This result is further evidence about the shortcomings of the existing assumption on the closed cycle for biomass-derived CO_2 emissions.

Concerning the OVIRF-based GWP_{bio}, values slightly higher than one can be obtained for TH = 20 years with rotation periods longer than 50 years. The reason can be seen in the corresponding graph in Fig. 3: in the first years soon after the emission, the OVIRF with r larger than 50 years has a slower decay than the decay from the Bern 2.5CC model (used as reference in the metric), thus affecting the GWP_{bio} for TH = 20 years. By contrast, the FIRF-based GWP_{bio} index ranges from 0 to 1, since the same IRF is used as $y(t)$ in Eqn (8) and reference in the metric. In this case, the climate impact derived from biomass combustion and subsequently reabsorbed in the ocean and terrestrial sinks can never be higher than the impact of the same quantity released by fossil fuel combustion or deforestation. Owing to the consideration of all the C cycles with terrestrial and ocean sinks, the FIRF method has the most consistent results which should be used in bioenergy LCA studies to estimate the climate impact of CO_2 emissions from biomass combustion.

Conclusions and next outlook

The work performed in this paper brings a new contribution to the rising discussion on the proper accounting of CO_2 emissions from biomass combustion in bioenergy systems. Even if perceived as urgent, a methodology able to quantify the effective climate impact of biomass-derived CO_2 emissions with unit-based indicators was not elaborated by LCA practitioners. The

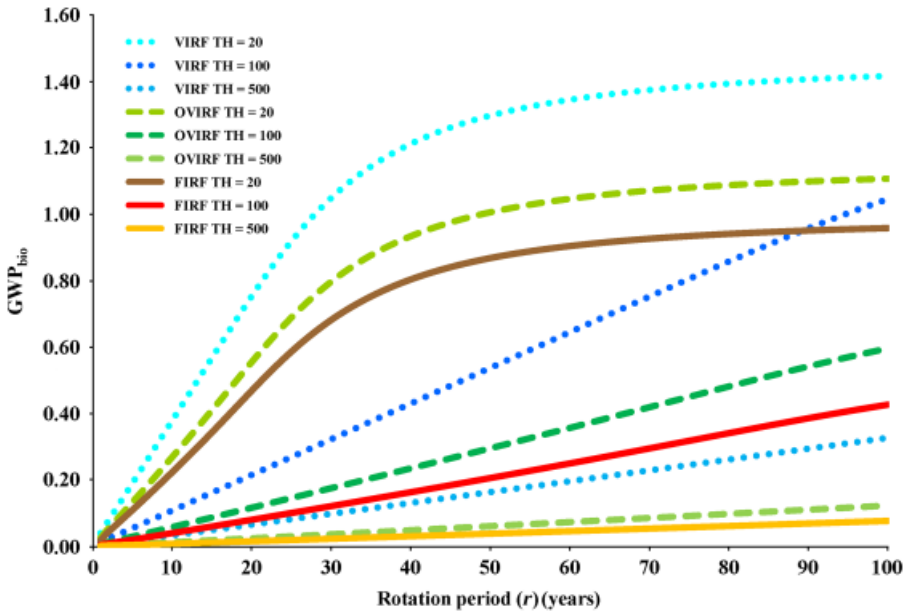

Fig. 5 GWP_{bio} for TH equal to 20, 100 and 500 years as a function of the biomass rotation period. GWP, global warming potential; TH, time horizon.

most important contributions of this work are the formulation of IRF for the atmospheric decay of CO_2 emissions from biomass combustion and the adoption of an index, the GWP_{bio}, to estimate their climate impact. Three methods were formulated, the VIRF, based on the closed cycle of bio CO_2, the OVIRF, which includes the ocean uptake, and the FIRF, which considers the full C cycle with ocean and terrestrial sinks. The FIRF-based GWP_{bio} is the most reliable and accurate option, given its complete consideration of all the C components and biogeochemical sinks. The GWP equivalency factor currently used for CO_2 emissions from biomass combustion in LCA should be revised: rather than a value of 0 (when the OECD convention is strictly followed) that underestimates the climate impact of the bioenergy system, or 1 (as performed by studies considering the initial CO_2 sequestration during plant growth or by studies based on forest C dynamics) that overestimate the climate impact of bio CO_2, this work proposes a figure between 0 and 1, depending on the rotation period of the biomass harvested. This is a first step towards the overcoming of the inadequacy of CO_2 accounting in LCA and the development of an accurate and standardized procedure.

This work acts as starting point for future research activities and investigation of specific case studies. In order to keep the focus of the paper on the development of a methodology to quantify the climate effect of bio CO_2 emissions, a schematic case based on one single rotation and with well defined initial conditions and parameters has been selected. The theoretical basis and calculations developed here can be expanded to model more specific case studies, with customized biomass growth curves, multiple rotations, particular management strategies, different starting conditions (e.g. afforestation rather than deforestation) or other specific factors. These outcomes can also be integrated within software tools modeling the climate effects of biomass production on terrestrial C pools and the environmental impact of bioenergy systems.

Besides LCA-based applications, of particular interest is the possibility to include the outcomes of this work in national GHG accounting mechanisms, so to revise the OECD convention presented at the beginning of this paper. The FIRF for bio CO_2 is suitable to be combined with the existing accounting of C stock changes to develop a robust and thorough C accounting framework. This application may have significant impacts on national GHG reporting for bioenergy production, and consequently needs to be investigated further to explore advantages and disadvantages. Implications at a policy decision level can be also relevant: new strategies taking into account the climate impact of CO_2 emissions from the temporary C loss needs to be established in order to reach the intended climate policy targets.

Acknowledgements

The work was funded by the Norwegian research council through the 'Bio-energy Innovation Centre – CenBio' (Cherubini, Strømman and Hertwich), 'Transport and Environment – Measures and Policies' (Peters and Berntsen) and 'Terrestrial C sequestration potential in Norway under present and future climate' (Peters). We thank Ottar Michelsen, Ryan Matthew Bright and Geoffrey Guest (NTNU) for the fruitful discussions and their critical review of this work.

References

Archer D, Kheshgi H, Maier-Reimer E (1998) Dynamics of fossil fuel neutralization by Marine $CaCO_3$. *Global Biogeochemical Cycles*, **12**, 259–276.

Blanke B, Delecluse P (1993) Variability of the tropical Atlantic Ocean simulated by a general circulation model with two different mixed-layer physics. *Journal of Physical Oceanography*, **23**, 1363–1388.

Börjesson P, Gustavsson L (2000) Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. *Energy Policy*, **28**, 575–588.

Caldeira K, Kasting JF (1993) Insensitivity of global warming potentials to carbon dioxide emission scenarios. *Nature*, **366**, 251–253.

Carpentieri M, Corti A, Lombardi L (2005) Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal. *Energy Conversion and Management*, **46**, 1790–1808.

Cherubini F, Strømman AH (2011) Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresource Technology*, **102**, 437–451.

Cramer W, Bondeau A, Woodward FI *et al*. (2001) Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. *Global Change Biology*, **7**, 357–373.

Enting IG, Wigley TML, Heimann M (2001). *Future emissions and concentrations of carbon dioxide: key ocean/atmosphere/land analyses*. Technical paper no. 31, CSIRO Division of Atmospheric Research.

Forster P, Ramaswamy V, Artaxo P *et al*. (2007) Changes in atmospheric constituents and in radiative forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. Solomon S), Intergovernmental Panel on Climate Change, Cambridge, UK.

Friedlingstein P, Fung I, Holland E, John J, Brasseur G, Erickson D, Schimel D (1995) On the contribution of CO_2 fertilization to the missing biospheric sink. *Global Biogeochemical Cycles*, **9**, 541–556.

Friedlingstein P, Müller JF, Brasseur GP (1994) Sensitivity of the terrestrial biosphere to climatic changes: impact on the carbon cycle. *Environmental Pollution*, **83**, 143–147.

Fuglestvedt JS, Berntsen TK, Godal O, Sausen R, Shine KP, Skodvin T (2003) Metrics of climate change: assessing radiative forcing and emission indices. *Climate Change*, **58**, 267–331.

Gerber S, Joos F, Prentice C (2004) Sensitivity of a dynamic global vegetation model to climate and atmospheric CO_2. *Global Change Biology*, **10**, 1223–1239.

Harmon ME, Ferrell WK, Franklin JF (1990) Effects on carbon storage of conversion of old-growth forests to young forests. *Science*, **247**, 699–702.

Houghton JT, Jenkins GJ, Ephraums JJ (1990) *Climate Change*. The IPCC Scientific Assessment, New York, USA.

Huo H, Wang M, Bloyd C, Putsche V (2008) Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. *Environmental Science and Technology*, **43**, 750–756.

IPCC (2006) *Guidelines for National Greenhouse Gas Inventories, Volume 4 – Agriculture, Forestry and other Land Use*. Intergovernmental Panel on Climate Change, Hayama, Japan.

Johnson E (2009) Goodbye to carbon neutral: getting biomass footprints right. *Environmental Impact Assessment Review*, **29**, 165–168.

Joos F (2003) The anthropogenic perturbation of atmospheric CO_2 and the climate system. In: *Recent research developments in biotechnology and bioengineering. Special Issue: Biotechnology and bioengineering of CO_2 fixation* (eds Bhattacharya SK, Mal TK, Chakrabarti S), Trivandrum, India, 183pp.

Joos F, Bruno M (1996) Pulse response functions are cost-efficient tools to model the link between carbon emissions, atmospheric CO_2 and global warming. *Physics and Chemistry of the Earth*, **21**, 471–476.

Joos F, Bruno M, Fink R, Stocker TF, Siegenthaler U, Le Quéré C, Sarmiento JL (1996) An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. *Tellus*, **48B**, 397–417.

Joos F, Prentice IC, Sitch S *et al*. (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Global Biogeochemical Cycles*, **15**, 891–907.

Kim S, Dale BE (2008) Life cycle assessment of fuel ethanol derived from corn grain via dry milling. *Bioresource Technology*, **99**, 5250–5260.

Kurz WA, Dymond CC, White TM *et al*. (2009) CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling*, **220**, 480–504.

Lashof DA, Ahuja DR (1990) Relative contributions of greenhouse gas emissions to global warming. *Nature*, **344**, 529–531.

Luo L, van der Voet E, Huppes G, Udo de Haes H (2009) Allocation issues in LCA methodology: a case study of corn stover-based fuel ethanol. *The International Journal of Life Cycle Assessment*, **14**, 529–539.

Maier-Reimer E, Hasselmann K (1987) Transport and storage of CO_2 in the ocean – an inorganic ocean-circulation Carbon Cycle Model. *Climate Dynamics*, **2**, 63–90.

Manomet (2010) Biomass Sustainability and Carbon Policy Study. In: *Massachusetts Biomass Sustainability and Carbon Policy Study: Report to the Commonwealth of Massachusetts Department of Energy Resources* (ed. Walker T), Contributors: Cardellichio, P, Colnes, A, Gunn, J, Kittler, B, Perschel, R, Recchia, C, Saah, D, and Walker, T. Manomet Center for Conservation Sciences, Brunswick, ME.

Marland G (2010) Accounting for carbon dioxide emissions from bioenergy systems. *Journal of Industrial Ecology*, **14**, 866–869.

Marland G, Schlamadinger B (1995) Biomass fuels and forest-management strategies: how do we calculate the greenhouse-gas emissions benefits? *Energy*, **20**, 1131–1140.

Masera O, Garza-Caligaris JF, Kanninen M *et al*. (2003) Modelling carbon sequestration in afforestation, agroforestry and forest management projects: the CO2FIX V.2 approach. *Ecological Modelling*, **164**, 177–199.

McGuire AD, Sitch S, Clein JS *et al*. (2001) Carbon balance of the terrestrial biosphere in the Twentieth Century: analyses of CO_2, climate and land use effects with four process-based ecosystem models. *Global Biogeochemical Cycles*, **15**, 183–206.

McKechnie J, Colombo S, Chen J, Mabee W, MacLean HL (2010) Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science and Technology*, **45**, 789–795.

Möllersten K, Grönkvist S (2007) All CO_2 is equal in the atmosphere – a comment on CDM GHG accounting standards for methane recovery and oxidation projects. *Energy Policy*, **35**, 3675–3680.

Moore B, Braswell BH (1994) The lifetime of excess atmospheric carbon dioxide. *Global Biogeochemical Cycles*, **8**, 23–28.

OECD (1991) *Estimation of greenhouse gas emissions and sinks*. Final report from the OECD experts meeting, 18–21 February, 1991, OECD, Paris.

Oeschger H, Siegenthaler U, Schotterer U, Gugelmann A (1975) A box diffusion model to study the carbon dioxide exchange in nature. *Tellus*, **27**, 168–192.

Petersen Raymer AK (2006) A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass and Bioenergy*, **30**, 605–617.

Prentice C, Heimann M, Sitch S (2000) The carbon balance of the terrestrial biosphere: ecosystem models and atmospheric observations. *Ecological Applications*, **10**, 1553–1573.

Quirin M, Gartner SO, Pehnt M, Reinhardt GA (2004). *CO_2 mitigation through biofuels in the transport sector: status and perspectives*. In: I. f. E. a. E. R. (IFEU) (Ed.), Main Report, Heidelberg, Germany. 57 pp.

Rabl A, Benoist A, Dron D, Peuportier B, Spadaro JV, Zoughaib A (2007) How to account for CO_2 emissions from biomass in an LCA. *International Journal of Life Cycle Assessment*, **12**, 281.

Randerson JT, Liu H, Flanner MG *et al*. (2006) The impact of boreal forest fire on climate warming. *Science*, **314**, 1130–1132.

Reijnders L, Huijbregts MAJ (2008) Biogenic greenhouse gas emissions linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans. *Journal of Cleaner Production*, **16**, 1943–1948.

Rodhe H (1990) A comparison of the contribution of various gases to the greenhouse effect. *Science*, **248**, 1217–1219.

Rossi S, Tremblay M-J, Morin H, Savard G (2009) Growth and productivity of black spruce in even- and uneven-aged stands at the limit of the closed boreal forest. *Forest Ecology and Management*, **258**, 2153–2161.

Schelhaas MJ, van Esch PW, Groen TA (2004). *CO2FIX V 3.1 – a modelling framework for quantifying carbon sequestration in forest ecosystems*. ALTERRA Report 1068, Wageningen, the Netherlands.

Schimel D, Alves D, Enting I *et al*. (1996) Radiative forcing of climate change. In: *Climate Change 1995. The Science of Climate Change* (eds Houghton JT, Meira Filho LG, Callander BA *et al*.), pp. 65–131. Cambridge University Press, Cambridge.

Schlamadinger B, Marland G (1996a) The role of forest and bioenergy strategies in the global carbon cycle. *Biomass and Bioenergy*, **10**, 275–300.

Schlamadinger B, Marland G (1996b) Full fuel cycle carbon balances of bioenergy and forestry options. *Fuel and Energy Abstracts*, **37**, 197–197.

Searchinger T (2010) Biofuels and the need for additional carbon. *Environmental Research Letters*, **5**, 024007, doi: 10.1088/1748-9326/5/2/024007.

Searchinger TD, Hamburg SP, Melillo J *et al*. (2009) Fixing a critical climate accounting error. *Science*, **326**, 527–528.

Searcy E, Flynn PC (2008) Processing of straw/corn stover: comparison of life cycle emissions. *International Journal of Green Energy*, **5**, 423–437.

Shine K, Fuglestvedt J, Hailemariam K, Stuber N (2005) Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*, **68**, 281–302.

Siegenthaler U, Joos F (1992) Use of a simple model for studying oceanic tracer distributions and the global carbon cycle. *Tellus*, **44B**, 186–207.

Siegenthaler U, Oeschger H (1978) Predicting future atmospheric carbon dioxide levels. *Science*, **199**, 388–395.

Strassmann KM, Joos F, Fischer G (2008) Simulating effects of land use changes on carbon fluxes: past contributions to atmospheric CO_2 increases and future commitments due to losses of terrestrial sink capacity. *Tellus B*, **60**, 583–603.

Swallow SK, Parks PJ, Wear DN (1990) Policy-relevant nonconvexities in the production of multiple forest benefits. *Journal of Environmental Economics and Management*, **19**, 264–280.

Tubiello FN, Oppenheimer M (1995) Impulse-response functions and anthropogenic CO_2. *Geophysical Research Letters*, **22**, 413–416.

UNFCCC (2003) *Estimating, reporting, and accounting of harvested wood products*. Technical paper FCCC/TP2003/7.

van der Voet E, Lifset RJ, Luo L (2010) Life-cycle assessment of biofuels, convergence and divergence. *Biofuels*, **1**, 435–449.

Wanninkhof R (1992) Relationship between wind speed and gas exchange over the ocean. *Journal of Geophysical Research – Oceans*, **97**, 7373–7382.

Werner F, Althaus H-J, Künniger T, Richter K (2003) Life Cycle Inventories of Wood as Fuel and Construction Material. Final report ecoinvent 2000 No. 9, EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH.