GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012) **4**, 576–587, doi: 10.1111/j.1757-1707.2011.01137.x

Zero, one, or in between: evaluation of alternative national and entity-level accounting for bioenergy

DAVID NEIL BIRD, NAOMI PENA, DORIAN FRIEDEN* and GIULIANA ZANCHI
Joanneum Research, Elisabethstrasse 5, A-8010, Graz, Austria

Abstract

Accounting for bioenergy's carbon dioxide (CO_2) emissions, as done under the Kyoto Protocol (KP) and European Union (EU) Emissions Trading Scheme, fails to capture the full extent of these emissions. As a consequence, other approaches have been suggested. Both the EU and United States already use value-chain approaches to determine emissions due to biofuels – an approach quite different from that of the KP. Further, both the EU and United States are engaged in consultation processes to determine how emissions connected with use of biomass for heat and power will be handled under regulatory systems. The United States is considering whether CO_2 emissions from biomass should be handled like fossil fuels. In this context, this article reviews and evaluates the three basic bioenergy accounting options.

1 CO_2 emissions from bioenergy are not counted at the point of combustion. Instead emissions due to use of biomass are accounted for in the land-use sector as carbon stock losses – a combustion factor (CoF) = 0 approach;
2 CO_2 emissions from bioenergy are accounted for in the energy sector – a CoF = 1 approach; and
3 End users account for all or a specified subset of CO_2 emissions, regardless of where geographically these emissions occur – 0 < CoF < 1.

Following short descriptions of the basic options, this article discusses variations to these options and uses numerical examples to illustrate the impacts of approaches at a local and international level. Finally, the alternative accounting systems are evaluated against general criteria and for impacts on selected stakeholder goals. General criteria considered are: (a) comprehensiveness, (b) simplicity, and (c) scale independence. Stakeholder goals reviewed are: (a) stimulation of rural economies, (b) food security, (c) GHG reductions, and (d) preservation of forests.

Keywords: bioenergy, carbon accounting, carbon neutrality

Received 25 July 2011; revised version received 15 September 2011 and accepted 23 September 2011

Introduction

In contrast to fossil fuel carbon stocks, biomass carbon stocks can be replenished relatively quickly by growing new biomass to replace biomass combusted for bioenergy. This is the basic reason why bioenergy can mitigate climate change. However, as has been pointed out by numerous authors, the current accounting system for greenhouse gas (GHG) emissions in operation under the Kyoto Protocol (KP) and EU Emissions Trading Scheme (EU-ETS) fails to capture the full extent of emissions caused by bioenergy. Consequently, nations and energy producers with reporting obligations tend to use more bioenergy than is justified by the amount of GHG emission reductions it achieves (Peters *et al*., 2009; Searchinger *et al*., 2009; Pingoud *et al*., 2010). This article poses the question: would an alternative accounting system lead to use of bioenergy more in line with the emission reductions it achieves?

Under the KP accounting system, no carbon dioxide (CO_2) emissions are counted in the energy sector when the biomass is combusted (zero emissions at point of combustion). Measurements of changes in carbon stock levels in the land-use sector are used as a proxy for measurements of combustion emissions, and the results from the land-use sector are reported in the accounting system. While this approach will correctly account for emissions if all nations report all carbon stock changes, developing countries do not report under the KP. In addition, some stock reductions are not reported in nations that have not elected Article 3.4 (i.e., have chosen not to include forest and agricultural management). To the extent that carbon stock losses are not reported, CO_2 emissions due to combustion of biomass will not be accounted for at all under the KP approach, even if

Correspondence: D. Neil Bird, tel. + 43 361 876 1423, fax + 43 316 9876 1423, e-mail: neil.bird@joanneum.at

*Correction added after online publication 27 October 2011: Author's name added the bioenergy is used in nations that have KP obligations.

Under both the KP and the EU-ETS, energy producers have a powerful incentive to use biomass for energy since they do not have to hold permits for these emissions. There is also an incentive to source the biomass from nations where changes in carbon stocks are not counted or from forests not covered by management reports. Bringing more nations and land-use sector emissions into the accounting system would alleviate this situation. However, there are other ways to bring use of bioenergy more in line with the emission reductions it achieves. In particular, increasing the responsibility of energy sector actors for bioenergy emissions holds promise. This can be done either through 1-combusiton factor or end user responsibility. This article reviews these two accounting approaches with current EU and US consultation processes on regulatory options for biomass used for heat and power underscoring the timeliness of such a review.

Methodology

This article explains three different approaches to accounting for emissions due to use of bioenergy that were described in Bird *et al.* (2010). Diagrams, text, and a numerical example are used to portray differences between the approaches. Following the explanations, the alternative approaches are evaluated against three general criteria. The evaluation builds on a landmark paper on accounting systems which recommended five criteria: accuracy, simplicity, scale independence, precedence, and incentives (Apps *et al.*, 1997). Accuracy has been renamed comprehensiveness over space and time to make clear the importance of correct accounting in both dimensions. Scale-independence is an issue because accounting systems may be applied by entities within a nation as well as at national or sub-national jurisdictional levels. We believe precedence was selected due to its contribution to simplicity and therefore consider it within simplicity. In this article, incentive issues are considered to be outcomes of accounting systems. Therefore, they are handled separately from the evaluation criteria. Incentives are considered in connection with three stakeholder goals: stimulation of rural economies, GHG reductions, and preservation of forests. These three goals can be used to represent a wider range of reasons for pursuing bioenergy due to synergies between seemingly disparate goals.

Explanations of different accounting systems

Figure 1 shows the physical flows of GHGs to and from the atmosphere and the transfer of biomass (as carbon, C) from a biomass producer to a consumer that occur when biomass grown and used for energy. Variations of this diagram will be used to illustrate where, in a particular approach, emissions are accounted for. Three physical GHG flows occur in connection with biomass production: CO_2 absorbed by plants, CO_2 oxidized by plants (both of which are shown as Bio-CO_2), and fossil-CO_2 and non-CO_2 emissions that occur during biomass production. There are also GHG emissions connected with conversion of biomass to a fuel and its transportation from the point of production to an initial biofuel purchaser. In Fig. 1, these are included in the producer's emissions. The biofuel purchaser, hereafter denoted as the consumer, has two streams: CO_2 from the combustion of biomass (bioenergy CO_2) and fossil-CO_2 and non-CO_2 emissions from combustion and distribution to an end user.

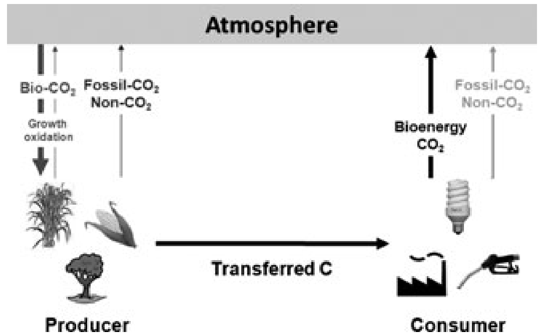

Fig. 1 Physical greenhouse gas emissions and flows of carbon in a bioenergy system.

Figures 2–4 illustrate three basic alternative philosophies that form the basis of all the approaches to accounting for emissions from use of bioenergy.

1 CO_2 emissions produced when biomass is burnt for energy are not counted at the point of combustion. They are accounted for in the land-use sector as carbon stock losses. We term this a *combustion factor* = 0 approach (CoF = 0).
2 CO_2 emissions produced when biomass is burnt for energy are accounted for in the energy sector. We term all such approaches *combustion factor* = 1 approaches (CoF = 1). Here, there are two variations; one in which uptake of CO_2 from the atmosphere by plants and soils is also accounted for and one in which these are not accounted.
3 End users are responsible for all or a specified subset of emissions that occur along the bioenergy value chain. We term these *value-chain* approaches. These approaches can be used to calculate a combustion factor between 0 and 1 ($0 < CoF < 1$).

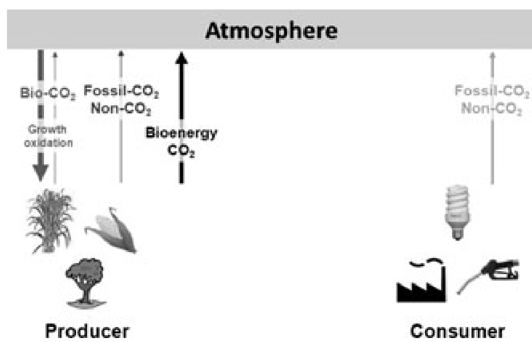

Fig. 2 Location of where the physical flows are theoretically accounted for in a 0-combustion factor approach.

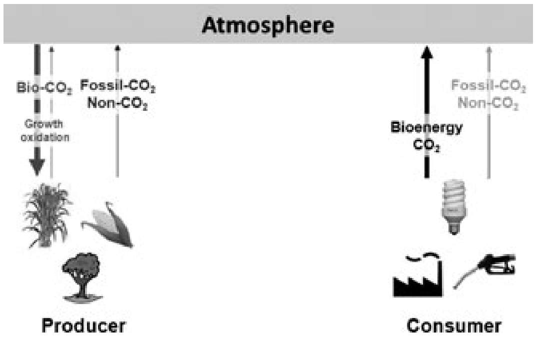

Fig. 3 Location of where the physical flows are theoretically accounted for in a 1-combustion factor approach.

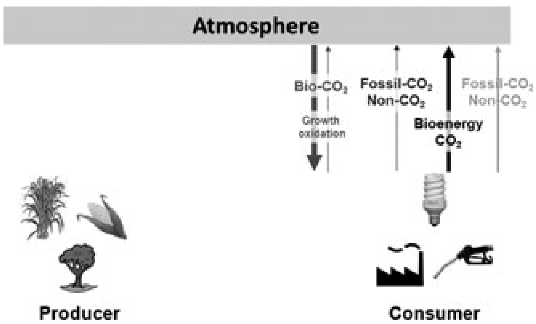

Fig. 4 Location of where the physical flows are theoretically accounted for in a value-chain approach.

*Combustion factor = 0 approaches*In a CoF = 0, approach emissions due to combustion of biomass are counted as carbon stock losses in the land-use sector (see Fig. 2). In this approach, emissions due to transport and conversion of biomass are accounted for outside of the biomass accounting system, i.e., in the fuel combustion or industrial process sectors as appropriate.

The Intergovernmental Panel on Climate Change (IPCC) methodology for calculating emissions from bioenergy, which was adopted under the KP, is an example of a CoF = 0 approach. The concept underlying this approach is that as long as sufficient biomass grows to replace the combusted biomass (Bio-CO_2 $\geq$ Bioenergy CO_2), bioenergy will not result in an increase of CO_2 emissions to the atmosphere. Atmospheric CO_2 increases only if harvesting exceeds growth. In this case, it is assumed that the carbon stock losses will be registered in the accounting system.

*Combustion factor = 1 approaches*The CoF = 1 accounting approaches treat CO_2 emissions from biomass exactly the same as emissions from fossil fuels. Emissions are accounted for in energy sector. Bio-CO_2 (uptake of CO_2 from the atmosphere) is counted by the producer. Emissions other than CO_2 resulting from combusting the carbon in the biomass are accounted for elsewhere in the system (Fig. 3). One can see that the location of where the physical flows would be accounted for in a CoF = 1 approach reflects the actual physical GHG emissions and flows of carbon (Fig. 1).

*Value-chain approaches*In value-chain approaches, GHG emissions and CO_2 removals that occur throughout all the production, conversion, transportation, and consumption processes are considered the responsibility of the consumer. Emissions that are accounted elsewhere in the system in the 0- and 1-combustion factor approaches (blue arrows) are included in the bioenergy account, and all flows appear on the consumer side of our schematic diagram (Fig. 4).

While sharing the life-cycle assessment (LCA) approach of considering impacts throughout a product's life, GHG emission value chains only consider GHG emissions. By not considering energy balances, process details, or other inputs or outputs, they are considerably simpler than full LCAs.

Emissions along the value chain can be used to generate a combustion factor between 0 and 1.[1] The atmospheric removals and emissions over the full production-through-use cycle are aggregated into a single number, percent or ratio. For example, if Bio-CO_2 equals 40 tonnes carbon (tC) removed from the atmosphere while 100 tC is emitted along the value chain, a factor of 0.6 could be applied at the point of combustion.

Value-chain approaches are prone to double counting. If the nation where biomass is produced accounts for GHG emissions throughout its economy, carbon stock losses and emissions due to fertilizer use, harvesting, processing, and domestic transportation emissions will already be counted in the respective sectors. If these emissions are then also included in value-chain accounts of entities using bioenergy, they would be counted twice. A system designed to avoid this problem is described below.

Variations to CoF = 1 and value-chain approaches

Two options under CoF = 1 approaches are referred to hear as 'Tailpipe' and 'Point of Uptake and Release' (POUR). Under a Tailpipe approach, the flow of CO_2 to the atmosphere from the combustion of biomass is counted so that emissions from bioenergy are treated in the same way as emissions from fossil fuels. Carbon stock changes are not measured in determining the impact of use of biomass for energy. However, if carbon stock reductions occur and are counted, this results in double counting.

The POUR approach avoids this potential for double counting while using a CoF = 1 approach. Under POUR, the total net CO_2 uptake by plants from the atmosphere is counted as negative emissions in the national report. Total net uptake includes carbon stock changes in the landscape plus carbon removed from the landscape, i.e., carbon embodied in biomass removed from the landscape for all purposes since this carbon also represents CO_2 removed from the atmosphere. The negative emissions counted for carbon in biomass combusted cancel out the positive combustion emissions, thus avoiding double counting.

[1]Theoretically factors outside the 0–1 range could result from a value-chain approach. However, it is assumed that if the factor were greater than 1, it is no likely that the biomass would be used for energy. Factors lower than 0 will only emerge if, after combustion, the CO_2 is sequestered, which would not influence the factor that would be used at the point of combustion.

In order for POUR to operate as described above where the producer nation does not account for its GHG emissions, a mechanism is needed to grant credits for net carbon uptake in such countries and enable credit transfer – presumably through entitling sales and purchases – to nations or entities with accounting obligations. Failing such a mechanism POUR collapses to Tailpipe where producing nations do not participate in the accounting system.

EU Renewable Energy Directive (EU RED) (European Union, 2009) and US Renewable Fuels Standard (US RFS2) (Federal Register, 2010) approaches include such restrictions use value-chain approaches to biofuels. Emissions along a biofuel's value chain are calculated to determine whether its emissions are sufficiently below those of fossil-fuel alternatives to qualify for use under a mandate. In addition to these calculations, both systems restrict sources or types of biomass, primarily in an attempt to avoid situations where substantial reductions in forest carbon occur to produce biomass for biofuels. In neither case is a combustion factor derived for application at the point of combustion.

In contrast to these systems, DeCicco (2009) proposes use of value-chain emissions to calculate an emission factor. Under this system, credits based on atmospheric removals are allocated to the biomass producer. After subtracting emissions due to cultivation – e.g. from fertilizer use – credits remaining are passed on to the processor. Credits remaining after subtraction of process emissions are passed on to a fuel distributor. All fuels are subject to a 1-combustion factor except insofar as net value chain credits support a lower factor.

A numerical example

In the example, a producer (nation, region, or individual) produces 83 200 t of wood pellets that are shipped to the consumer, who uses them to produce 1.0 PJ of electricity.[2] The calculation is limited to the emissions for this activity only (wood → pellets → electricity) in that occur the year of production only. There are emissions along the entire value chain because the wood must be harvested, dried, pelletised, and transported to the consumer before combustion. In the example, it is assumed that the pellets are shipped from the producer to the consumer by sea and that the consumer's facility is on the coast. Values for harvesting, processing and transportation emissions are based on values for pellets produced in Canada and shipped to Sweden (Magelli *et al*., 2009). As it is assumed that the consumer's facility is on the coast, no transportation emissions are allotted to the consumer.

The biomass is assumed to come from a forest that has been sustainably managed for multiple decades (the average harvest level is less than the net annual increment). To meet increased demand for bioenergy, the rotation length is shortened (frequency of harvest increases), which results in a period of time when the harvest exceeds the net annual increment. After this time, the management returns to a sustainable management regime although with a shorter harvest rotation. In the example, the amount harvested (87 537 Mg – the amount of biomass required to make the wood pellets) exceeds forest growth (i.e. 80 803 Mg).[3] In addition, 5% of the harvested biomass (e.g. harvesting residue left in the forest) is not shipped to the consumer. For simplicity in accounting for GHG emissions, we assume that this residue is burnt, for example, by the local population for heating and cooking. The net photosynthesis is calculated as the stock change plus the amount of biomass removed.

Table 1 illustrates the total emissions in any given year that will be counted, as well as which emissions are counted by each party, under the above options. It is assumed that the consumer is in a nation with GHG accounting obligations but the producer may or may not be.

The row 'Producer total' indicates the total GHG emissions that will be counted in a Producer nation if the nation has an accounting obligation. 'Consumer total' shows the total GHG emissions that will be counted if only the consumer is in a nation with GHG obligations. 'Global total' indicates the GHG emissions that will be accounted for if both producer and consumer have GHG obligations.

Under the KP net photosynthesis is ignored. The producer accounts for the stock loss, harvesting emissions and transportation of the pellets to the coast if it has an accounting obligation. However, if the producer is in a nation without accounting obligations (non-Annex-I country or Annex-I country that has not opted to report under Article 3.4), none of this will be accounted for. As shown in the final row, in this case no emissions will be counted since the consumer nation does not account for emissions when it combusts the biomass.

Under a Tailpipe approach, neither photosynthesis nor carbon stock changes are counted. As a result, if only the consumer accounts, over 152.000 megagrams of CO_2 (Mg CO_2) will be reported, over twice the actual emissions of close to 72.500 Mg CO_2. If both producer and consumer report, total emissions accounted will be even higher.

In POUR the producer records an estimate of net photosynthesis within its bioenergy account if it is in a nation with accounting obligations. Emissions due to harvesting, processing, and domestic transport will be reported elsewhere in his or her account. Taken together with the net photosynthesis, the producer would have net removals from the atmosphere (a net sink) of some 115 103 Mg CO_2. The consumer reports 152 460 Mg CO_2 for a combined report of 37 347 Mg CO_2. In this case, the only emissions not reported are those due to international transportation.

Where the producer does not have a reporting obligation, POUR reverts to Tailpipe. However, a primary motivation for moving to a POUR approach is to insure that carbon stock losses are accounted for without unduly discouraging use of bioenergy. To accomplish this, it is envisioned that a mechanism would be established to transfer net sequestration credits from any producer nation to nations with GHG reporting obligations. The prospect of receiving credits may serve to entice producing nations to participate in the system, with attendant

[2]The electricity generation has an assumed 65% efficiency, and the energy content of the wood is 18 GJ Mg^{-1}.

[3]It is for this reason that the emissions from wood consumption (152 460 t CO_2) are more that the removals from forest growth (148 139 t CO_2).

Table 1 Numerical example: reporting under different accounting approaches (Mg CO_2). There are two values in the global total under value chain to indicate the effect of double counting if both producer and consumer nation report emissions in producing nation. na, not applicable; in cons., in consumer account

Producer component	Actual	KP	Tailpipe	POUR	Value chain	DeCicco
Net photosynthesis	**−148 139**			**−148 139**	**in cons.**	**in cons.**
Stock change		**12 345**	**na**	**na**	**na**	**na**
Harvesting and processing						
Collection and processing	22 540	22 540	22 540	22 540	in cons.	22 540
Process waste (burnt)	8024		8024	8024	in cons.	8024
Subtotal	**30 564**	**22 540**	**30 564**	**30 564**		**30 564**
Transportation						
Transportation	2473	2473	2473	2473	in cons.	2473
Producer total	**−115 103**	**37 357**	**33 037**	**−115 103**	**0**	**33 037**
Consumer component						
Wood consumption	152 460	0	152 460	152 460	72 488	
Consumer total	**152 460**	**0**	**152 460**	**152 460**	**72 488**	**39 452**
Other components						
International transportation	**35 131**	**na**	**na**	**na**	**in cons.**	**in cons.**
Global total	**72 488**	**37 357**	**185 497**	**37 357**	**72 488 or 105 525**	**72 488**
Global total if producer does not participate		**0**	**152 460**	**152 460**	**72 488**	**72 488**

Bold values are totals for a sector.

responsibilities to track net removals and carbon stock changes across their land-use sectors.

Value-chain approaches transfer responsibility for all emissions to the user (consumer). Full emissions, including those due to international transportation, are thus reported regardless of whether a producer nation has a GHG obligation. A nonsophisticated value-chain approach (column 6) can lead to double counting if both the consumer and producer report harvesting, processing, and transportation emissions in the producing nation. In this case, more emissions are reported (105 525 Mg CO_2) than actually occur. In the more sophisticated system shown in column 7, this does not occur. In this system, the correct emissions will be reported regardless of whether the producer nation has a reporting obligation. If it does, that nation will report 33 037 Mg CO_2 and the consumer will report 39 452 Mg CO_2. If the producer does not report, the consumer will report the full 72 488 Mg CO_2 that arise in the example.

The criteria

This article evaluates the alternative accounting systems using three criteria: comprehensiveness over space and time, simplicity, and scale-independence. Comprehensiveness over space and accuracy in time is a measure of environmental integrity and is here used to refer to the degree to which an accounting system counts emissions once and only once.

Following Einstein's dictum, it is always preferable to use a system that is 'as simple as possible, but no simpler'. Simplicity is a main reason that CoF = 0 factor approach was recommended and selected. The approach requires only the measurement of carbon stock changes, for which there is considerable experience from forest inventories. However, under real-world conditions – i.e., the fact that many nations do not report under the KP – this approach may be 'simpler than possible' given the importance of achieving reasonable coverage over space.

Scale-independence encompasses not only the ability for a system to be used at varies scales but also the compatibility of results when this is done. Scale-independence is important because accounting systems may be used not only at the national level but also at sectoral levels and by entities subject to GHG limitations. Scale-independence is particularly challenging in cases where measurements of forest-carbon stock change form part of the system because such measurements give very different results at different scales. For instance, whereas annual forest regrowth at the national or landscape level can exceed or fully compensate for removals for bioenergy, this cannot happen at the stand level within an accounting period. Consequently, while a nation might report no net emissions due to use of bioenergy, an entity whose biomass came from a particular forest might report emissions.

Incentives evaluation

This article evaluates accounting approaches from the perspective of their impact on three goals that generally are pursued in conjunction with use of bioenergy: increase energy security, stimulate rural economies, or reduce GHG emissions. Food security is an issue for many nations, and stakeholders may also be interested in preserving forests and maintaining habitat and other environmental services, including in the context of reducing vulnerability to climate change. While some goals are generally mutually supportive or operate jointly, other goals tend to compete with one another. Goals that tend to operate jointly are food security, energy security, and stimulation of rural economies. These goals are thus handled together in this article.

Promotion of these goals generally seems to threaten preservation of forests and linked environmental services. For example, in absence of an increase in crop yield, use of biomass for energy may reduce biomass available for food and cause an expansion of cropland into forests. Therefore, preservation of forests is handled separately. Use of bioenergy to achieve GHG goals tends to threaten both food security and forest preservation, while working jointly with energy security and stimulation of rural economies. For these reasons, it also is treated separately.

Results

This section first looks at the impacts of the various systems on afforestation, deforestation, and emissions globally. Following this, the approaches are evaluated against the three criteria and then in regard to their impacts on national and stakeholder goals.

Global implications

To illustrate the global implications of the different accounting options, we will use an estimate of the global afforestation, deforestation and forest management and emissions that result from the GLOBIOM model (Havlík *et al.*, 2011). GLOBIOM provides estimates of land-use competition between the major land-based production sectors and assesses the land-use change (LUC) impacts of biofuel production scenarios in terms of afforestation and deforestation. This study developed the LUC events for four future scenarios of biofuel production using a partial equilibrium economic model. The four biofuel scenarios are as follows:

a. No biofuels are produced
b. Baseline (60% of biofuels that are produced are first generation and 40% are second generation);
c. Only first generation biofuels are produced; and
d. Only second-generation biofuels are produced.

As well, for the second-generation biofuels, three options were evaluated. Second-generation biofuels are created from short rotation forestry on:

i agricultural land;
ii marginal land; or from
iii existing forest lands.

Havlík *et al.* (2011) estimated the CO_2 emissions from LUC for the live biomass only assuming that agricultural practices do not have an impact on soil carbon emissions, and in the case of deforestation, the total carbon contained in above and below ground living biomass is emitted.

For the purposes of this article, we will focus on their results from the baseline scenario with the option that the biomass for second-generation biofuels comes from existing agricultural land. To the emissions from LUC, we add the emissions due to changes in dead wood litter and soil organic carbon. These emissions/removals are calculated as the difference of carbon stock in each of the three pools, before and after conversion. The assessment has been made based on default values provided in the 2006 IPCC Guidelines (IPCC, 2006). Default values are provided for carbon stocks in each pool and for each land use. The calculations are done at the regional level for eleven regions (Central-East Europe, Former Soviet Union, Latin America, Mid-East and North Africa, North America, Other Pacific Asia, Pacific OECD, Planned Asia-China, South Asia, sub-Saharan Africa, Western Europe).

Afforestation considers only conversion to short rotation plantations, whereas deforestation is the conversion of natural or managed forests to other land uses, such as cropland and grassland. It is assumed that changes in the litter and dead wood pool occur only with deforestation, whereas no change is assumed in the other cases. A carbon loss equal to the amount of carbon in the litter and deadwood is accounted for when a forest is cut and converted to cropland or grassland. This assumption is based on an IPCC Tier 1 approach, which considers no accumulation of litter and deadwood in cropland and grassland. Therefore, deforestation produces a loss of carbon in these two pools. Initial values of litter and deadwood carbon in forests were derived from table 2.2 of the 2006 IPCC Good Practice Guidance (IPCC, 2006) and table 4.2.2 of the 2003 IPCC Guidelines (IPCC, 2003). Regarding afforestation, the data only include conversions to short rotation plantations which accumulate very little litter and deadwood compared to cropland or grassland. Due to this reason, we conservatively assumed that no carbon is accumulated in litter and deadwood when land is converted to short rotation plantations. The emissions/removals in soil are calculated based on equation 2.25 and default factors in the 2006 IPCC Guidelines. According to this method, the carbon stock in the soil, under a specific land use, is calculated by first selecting a so-called reference soil carbon stock (SOCREF, table 3.3, IPCC, 2006). The SOCREF represents the carbon stock in reference conditions, i.e. native vegetation that is not degraded or improved. The SOCREF is the value that we used as soil carbon stock in Forestland. For other land uses, the soil carbon stock is calculated by multiplying the SOCREF for default factors that are specific for each land use, land management and level of organic inputs (tables 5.5, 5.10, and 6.2, IPCC, 2006). Default SOCREF values were chosen among the figures reported for high activity clay soils which include most of the existing soil types.

Finally ,we include estimates of the GHG emissions from the cultivation, processing, transport and distribution of biofuels, the non-LUC components (to the emissions due to LUC. For example, if corn is transformed into ethanol, then the non-LUC components are the emissions for using machinery to plow the land, transport the biomass to the ethanol plant, and distribute the ethanol to the consumer. As well, there are emissions from the use of inorganic nitrogen-based fertilizers that must be included. These emissions are usually included in a LCA of the impacts of biofuels. The emission factors are listed in Table 2. See Bird *et al.* (2011) for a complete discussion of the calculation methodology.

Figure 5 shows graphically the cumulative emissions from biofuels to 2030 by region under different accounting systems. It shows that under the IPCC accounting system (unmodified CoF = 0), consuming regions (CPA, NAM, SAS, and WEU) benefit greatly and will claim an emission reduction. On the other hand, Latin America, the modeled main producer, is burdened with a large amount of emissions under the IPCC approach. Using POUR accounting, Latin America still has large emissions, but it does not underwrite the emission reductions of the consuming regions. Since there is so large a swing in emissions, it is clear that if POUR is adopted, then emission targets would need to be completely renegotiated.

Evaluations against criteria

Comprehensiveness over space and time. Under conditions in which carbon stock reductions in developing countries are not accounted for within a GHG limitation regime, the CoF = 0 approach rates poorly in terms of comprehensiveness over space. Emissions at the point of combustion of biomass are not counted anywhere in the world, and emissions due to carbon stock reductions are counted only in nations that have accepted GHG limitations under the KP.

CoF = 1 approaches are significantly more comprehensive than unmodified CoF = 0 approaches. If the biomass producing nation does not participate in accounting, uncounted emissions include those from oxidation of biomass left in forests, soil carbon losses, and decay of biomass that was harvested but not converted for use for bioenergy. These are much smaller than emissions that fail to be counted under the same circumstances under an unmodified CoF = 0 approach.

However, if net atmospheric uptake of CO_2 by the land sector in a producer nation is not counted, accuracy will not be achieved. The inaccuracy will be one of over-counting, rather than under-counting emissions, except where drainage of wetlands occurs. In this case, both Tailpipe and POUR may underestimate emissions. As noted earlier, without a mechanism to grant and transfer credits for net atmospheric uptake, POUR reverts to Tailpipe, removing the motivation to use POUR. With such a mechanism accounting will be accurate over both time and space to the extent that credits are transferred to entities with obligations.

The comprehensiveness of value-chain approaches is different than for the CoF = 0 or 1 approaches. On the one hand, such systems tend to be quite comprehensive because they include in the bioenergy account emissions not included in the other approaches, e.g., emissions due to biomass cultivation, its conversion to an energy product, and its transportation to users. However, the spatial coverage of the EU RED is not high. First, it does not include emissions on land that does not change its status. This approach is prone to spatial omissions because, for instance, a forest might move from 80% tree coverage to 50% tree coverage while still remaining its forest status. The US RFS2 approach is not prone to these omissions because wood, except for residues and precommercial thinnings, can only come from natural forests threatened by fire. Second, the EU RED does not include emissions due to indirect land-use change (iLUC), and its attempt to manage these through an incentive mechanism is unlikely to be successful(Lange, 2011). The US RFS2 has attempted to include iLUC by using modeling to estimate the amount associated with each biomass-conversion combinations, e.g., ethanol from corn and ethanol from sugar cane. To the degree

Table 2 Emission factors for life-cycle emissions from biofuels. Emissions do not include combustion or land-use change. Ranges are taken from the range reported in various life-cycle assessment studies. The variation may be caused by differences in system boundaries, cultivation practices and crop yields, use of co-products, allocation of emissions to co-products, etc. For more information, see Cherubini *et al.* (2009)

Fuel	Emissions (g CO_2 eq MJ^{-1})	Range (%)	Source
Biodiesel, palm	54.0	± 35	European Union (2009)
Biodiesel, rape	46.0	± 35	European Union (2009)
Biodiesel, soy	50.0	± 35	European Union (2009)
Biodiesel, wood, farmed	4.0	± 57	European Union (2009)
Ethanol, cane	24.0	± 20	European Union (2009)
Ethanol, corn	37.0	± 30	European Union (2009)
Ethanol, wood, farmed	6.0	± 33	European Union (2009)

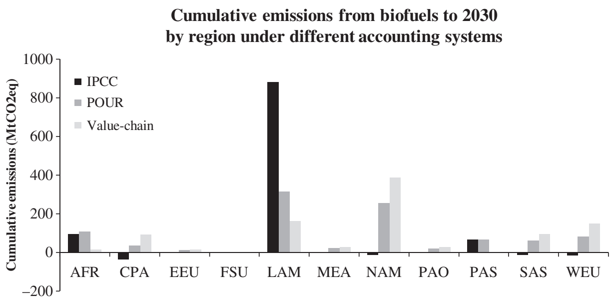

Fig. 5 Cumulative emissions due to biofuels to 2030 by region under different accounting systems. Abbreviations: AFR, sub-Saharan Africa; CPA, centrally planned Asia; EEU, Central and Eastern Europe; FSU, Former Soviet Union; LAM, Latin America; MEA, Middle East and North Africa; NAM, North America; PAO, Pacific OECD; PAS, other Pacific Asia; SAS, South Asia; WEU, Western Europe. Calculations are made by the authors but are based on data from Havlík *et al.* (2011). Please see the body of this article for details of the calculations.

that such modeling is accurate, its spatial coverage should be high.

The EU RED due to its focus on biofuels and the likelihood they come from annual crops has not addressed issues of timing. The US RFS2 attempts to achieve a reasonable degree of accuracy of timing through its restrictions to annual crops, residues and wood from plantations established as of 2007 and areas at high risk of fire. How well this will function will only be clear once significant amounts of woody biomass are used for biofuels.

Simplicity. The tailpipe system is probably the simplest of all approaches, requiring only that bioenergy emissions or the amount of biomass consumed for bioenergy be measured and converted to CO_2. Due to the overestimation that occurs, however, it is unlikely to be adopted. A POUR approach has better chances of adoption but is more complicated. Under the real-world circumstances of partial adoption of GHG limitation obligations, however, a POUR-type approach may be 'as simple as possible' as it ensures that emissions due to combustion of biomass in nations with GHG obligations are counted even if attendant stock reductions are not.

Point of Uptake and Release requires measuring carbon stock changes and reporting amount of biomass removed from the landscape in the producing nation plus measuring bioenergy combustion emissions in the consumer nation. The approach will raise challenges when applied to products that can be used either for food, feed, or fuel. As there is no suggestion to date that emissions due to human food consumption be included in GHG obligations, carbon stock changes due to production of, e.g., oils, sugar crops, and grains used for food would need to be separated out from carbon stock changes due to production for feeds, energy, or other products whose emissions will be counted where and when they occur. An additional complication is that since use of oils or grains may only be determined in the consuming nation, it will be necessary to track origin of dual-purpose biomass. This is necessary under POUR to determine the amount of carbon from a producing country embodied in nonfood products.

Value-chain approaches are more complicated than 0- and 1-combustion factor approaches due to their high data needs. They require information not only on biomass and attendant emissions but also information on emissions due to cultivation, conversion, and transportation used for a particular biofuel type or batch. Such information is needed from each nation that is a source of biomass.

Scale independence. It was expected that the CoF = 0 approach would be scale-independent as carbon stock levels can be measured from the stand level up to the national level. However, measurements of forest-carbon stock changes give very different results at different scales. Thus, the CoF = 0 approach has not turned out to be scale-independent. The POUR approach shares this weakness, but the tailpipe method is fully scale independent.

Value-chain approaches are not inherently scale-independent. They can only achieve this through use of national-level estimates of GHG emissions at each step along the value chain together with assumptions regarding the share of such emissions attributable to each batch of a biofuel. Given that, as previously mentioned, the destiny of agricultural products may only be determined in the consumer nation, this could prove extremely challenging. The value chains used in the EU RED and the US RFS2 are both batch-based and resulting emission calculations do not enter into national GHG accounting.

Summary. Table 3 summarizes the above evaluation of accounting approaches against the chosen criteria. While Tailpipe performs relatively well against all criteria, due to the over counting of emissions it may not be practical. The next best option is POUR which is more comprehensive than 0-combustion approaches and less complex than value-chain approaches. It shares the scale-independent problems of CoF = 0 approaches. Value-chain approaches are rated lower because of their complexity.

Accounting systems can support or hinder stakeholder goals because they tend to provide incentives or disincentives for specific actions. For example, we have already suggested that 0-combustion factor accounting approaches provide strong incentives for energy consumers to use bioenergy to meet GHG obligations, particularly if the carbon stock losses occur in another country or are uncounted.

Impacts of accounting system on stakeholder goals

Stimulation of rural economies and food security. A CoF = 0 factor approach provides a strong stimulus to use bioenergy. This stimulates production of both agricultural and forest biomass (Cortez *et al*., 2010). However, this stimulus may result in dedication of food and feed crops to energy and food and feed price increases. Dedication of food and feed crops to energy may reduce food security and lead to increased need for food imports in nations where agricultural supply is not sufficient to meet both demands (Pimental *et al*., 2009). Price increases tend to benefit farmers but can burden general populations, particularly its poorer segments.

Having the energy consumer account for GHG emissions from bioenergy combustion, as happens under CoF = 1 approaches, removes the incentive to use more bioenergy than justified by the emission reductions it achieves. Since in most applications biomass results in more CO_2 emitted per unit of energy produced than fossil fuels, use of bioenergy may be discouraged where entities are faced with GHG reduction obligations. As a consequence, the CoF = 1 approaches tend to decrease demand for biomass for energy. Thus, they neither stimulate rural economies nor result in food and feed prices increases or food security difficulties. The Tailpipe characterized by all of the effects. The POUR approach may overcome the lack of stimulation to rural economies through a mechanism that provides credit for atmospheric removal of CO_2 by biomass. The extent to which credits would overcome the disincentive to use bioenergy, and thus stimulate rural economies would depend on details of the transfer rules. Thus, until such a program is designed, the impacts cannot be evaluated.

Value-chain approaches have been implemented in conjunction with mandates to reduce GHGs and the mandates rather than the accounting system are driving increased use of bioenergy and thus stimulating rural economies. Insofar as the goal of value-chain approaches is to align use of bioenergy with its emission consequences, value-chain approaches are more likely to resemble CoF = 1 than CoF = 0 approaches.

GHG reductions. Because of the current and expected incomplete participation in binding GHG targets, together with the fact that bioenergy producers incur no costs for their emissions, the CoF = 0 accounting approach fails to promote GHG reductions. In fact, it may actually result in more emission than the continued use of fossil fuels (Havlík *et al*., 2011). The CoF = 1 approaches can be effective ways to control GHG emissions because bioenergy producers do incur costs for emissions. The fact that combustion of biomass generally generates more CO_2 emissions to produce a unit of energy than the combustion of fossil fuels increases the difficulty of achieving the goal of reducing GHG emissions by using woody biomass in the short term (Walker *et al*., 2010; Zanchi *et al*., 2010; McKechnie *et al*., 2011; Repo *et al*., 2011). A POUR approach with a crediting mechanism might be particularly effective in addressing emissions from the land sector. If a crediting mechanism induces nations without GHG obligations to track net atmospheric removals as a condition for receiving and selling credits, there would be a powerful incentive for them to move to practices in which carbon stock reductions are lower than biomass removed from the landscape, e.g., less is harvested annually than grows.

Making users responsible for value-chain GHGs can translate into incentives both to produce and to pur-

Table 3 Evaluation of accounting approaches against criteria

	Criteria			Combined	
Accounting approach	Space and time	Simplicity	Scale	Evenly weighted	Space and time double weight
Combustion factor = 0 approaches (CoF = 0)					
Unmodified	Low	High	Low	Medium	Medium
Existing+emissions correction	Low	Low	Low	Low	Low
Existing+policy overlay	High to low	Medium to low	Low	Medium to low	High to low
Combustion factor = 1 approaches (CoF = 1)					
Tailpipe	Medium	High	High	High	High
POUR	High	Medium	Low	Medium	Medium
Value-chain approaches					
All	Very high	Low	Low	Medium	High

chase biomass with the lowest GHG profiles. This, however, only will happen under value-chain approaches where the profile directly impacts costs, as would happen under a DeCicco-type system where the lower the GHG profile the fewer permits to emit required. Under these circumstances, value-chain approaches may be the most effective way of reducing GHG emissions associated with the use of bioenergy.

Preservation of forests. The extent to which an accounting approach preserves forests is often closely related to its ability to reduce GHG emissions. The 0-combustion factor approach, for example, does neither very successfully, whereas Tailpipe does both effectively.

As the tailpipe approach discourages the use of bioenergy, it can be considered supporting preservation of forests just as it supports reductions in GHG emissions from biomass. In POUR, on the other hand, credits may be received for removals embodied in harvested wood. This leads to the assumption that there would be a strong incentive to harvest. However, credits are received only for carbon in wood sold minus carbon stock losses. Hence, POUR may provide an incentive to sustainable forest management. The actual impact of POUR on forest preservation could, however, only be determined once a program with sufficient detail was developed to enable economic analyses well beyond the scope of this study.

The impact of a value-chain approach to bioenergy on forests will depend greatly on the specifics of its design as well as whether emissions calculated along the value chain are used to determine a combustion factor or it is used in conjunction with mandates. The EU RED approach allows significant degradation of natural forests and even replacement of natural forests with plantations as long as they meet specific criteria. The US RFS2, by restricting use of woody biomass to residues, slash, precommercial thinnings, and forests planted by hand or machine on land cleared prior to 2007 is very likely to prevent loss or degradation of forests.

A major issue is how a value-chain approach will deal with the problem that arises in the case of woody biomass: emissions occur in the near term but compensating regrowth, particularly at the batch level, can take decades to centuries. If little or no attention is paid to this problem, as appears to be the case in the EU RED, a value-chain approach may not preserve forests effectively. Currently, the mandates play a larger role in the impact on forest preservation, than the accounting system.

Summary. Table 4 provides a qualitative summary of our evaluation of accounting approaches in support of stakeholder holders' goals. We find that the unmodified CoF = 0 approach behaves very poorly. A CoF = 0 approach restricted to trading partners that have committed to a GHG limitation rates well across all goals. However, given that it would leave most nations outside of the system, as well as potential objections on free trade grounds, it may not be a desirable solution.

The Tailpipe approach does well for most goals but given its strong discouragement of use of bioenergy together with its over counting of emissions it may also not be a desirable choice. A POUR approach has potential but the design of a crediting and credit-transfer mechanism, as well as the response of nations without GHG obligations, would be critical in performance characteristics. Similarly, a DeCicco-type value-chain approach seems to have considerable potential. As a value-chain approach it brings use of bioenergy into line with its GHG emissions. Thus, while it will encourage use of bioenergy where GHG profiles are favorable, it is unlikely to encourage bioenergy at levels that would unduly affect food and feed prices.

Discussion and conclusions

The current accounting system for emissions from bioenergy gives entities with GHG obligations an incentive to use bioenergy at the expense of maintenance of carbon stocks. In this article, we describe and examine alternative approaches that could potentially redress this system weakness.

The problem arises because the KP's accounting of bioenergy is a '0-combustion factor' (CoF = 0) approach. Emissions from the combustion of biomass for energy are not accounted in the energy sector, but in the land-use sector as carbon stock losses. However, in reality, many carbon stock losses are not accounted for. Many countries do not have GHG targets and some countries that have them do not include carbon stock changes in forests remaining forests, or even from deforestation where net forest area remains steady or increases. In this way, the KP provides an incentive for KP compliant nations to obtain biomass for energy from nations without KP obligations or other sources not accounted for. The EU-ETS in particular provides energy producers with a powerful incentive to use bioenergy regardless of its carbon stock implications as carbon stock changes play no part in the EU-ETS.

This article describes alternative approaches to accounting for bioenergy emissions and proposes that all alternatives fall into one of three categories: (1) application of a 0-combustion factor to bioenergy emissions at the point of combustion (the current approach); (2) CO_2 emissions at combustion are similar to fossil fuels (1-combustion factor approach); and (3) value-chain approaches in which bioenergy consumers are responsible for net GHG emissions generated along the bioenergy value chain and these emissions can be used to calculate a combustion factor between zero and one.

This article examines several options within each of these categories, including use of policy overlays or correction factors in connection with a CoF = 0 approach; counting only emissions (Tailpipe) or also counting atmospheric uptake of CO_2 (POUR) within the CoF = 1 group; and value chains that do and do not use the calculated emissions to determine a combustion factor. The value chains used in the EU RED and US RFS2 do not use calculated emissions to determine a combustion factor, whereas an approach proposed by DeCicco does.

This article points out that the value-chain approaches differ from the other two types of approach in two significant ways. They encompass not only emissions from combustion of biomass and carbon stock losses but also emissions from cultivation of biomass and its conversion and transportation. Second, unlike any of the 0- or 1-combustion factor approaches, they hold a consuming nation responsible for emissions that occur outside of its national boundaries.

Finally, this article evaluates the accounting options against general criteria and selected stakeholder goals. The general criteria are comprehensiveness over space and time, simplicity, and scale-independence. Stakeholder goals are stimulation of rural economies, food prices, and energy security; reductions of GHG emissions; and preservation of forests.

With regard to accuracy of accounting over space and time, value chain and combustion CoF = 1 approaches tend to perform better than CoF = 0 approaches, significantly increasing the fraction of emissions due to bioenergy captured in the accounting system. Emissions that would not be included in CoF = 1 systems are those due to soil and litter pool carbon losses and in the case of drainage of wetlands additional GHG emissions. However, there is a trade-off. Except for Tailpipe, CoF = 1 and value-chain approaches are not as simple as the unmodified 0-combustion factor approaches.

In general, CoF = 0 approaches, by encouraging use of bioenergy, tend to stimulate rural economies but do poorly against other goals, with the exception of restricting trading partners to nations with GHG limitation obligations. The CoF = 1 options have the opposite tendencies. They tend to discourage use of bioenergy and thus fail to stimulate rural economies. POUR may overcome this through inclusion of a credit and credit-transfer mechanism. Producer countries would receive credits for net atmospheric uptake of CO_2 which could be sold to bioenergy consumers. If such a mechanism were available to all nations, POUR could be effective in controlling GHG emissions because it would encourage maintaining carbon stocks while providing biomass for energy. Value-chain approaches are theoretically neutral between use of bioenergy and continued use of fossil fuels and therefore would tend not to encourage use of bioenergy due to its high emissions per unit of energy produced. However, to date, value-chain approaches have been used in conjunction with mandates that drive use of bioenergy, and the specifics of the programs have determined the outcomes on stakeholder goals.

Table 4 Qualitative review: accounting options vs. stakeholder goals. The evaluation of POUR assumes mechanism to award and transfer credits from producer to consumer

Accounting system	Stimulate rural economies	Protect food security	Reduce GHG emissions	Preserve forests
Combustion factor = 0 approaches (CoF = 0)				
Unmodified	High	Low	Low	Low
Existing + emissions correction	Lower than unmodified	Higher than unmodified	Uncertain	DPD
Existing + limited sources	Likely high	Uncertain	DPD	DPD
Existing + limited trading partners	High	High	High	High
Combustion factor = 1 approaches (CoF = 1)				
Tailpipe	Low	High	High	Low
POUR	DPD, potentially high	Potentially low	DPD, potentially high	DPD, potentially high
Value-chain approaches				
EU RED	DM	Low	Medium	Medium
US RFS2	DM	Low	High	High
DeCicco-type	Medium to high	Medium	High	Likely high

POUR, Point of Uptake and Release; GHG, greenhouse gas; DPD, depends on program details; DM, depends on mandate.

Both POUR and a DeCicco approach seem to hold considerable promise to do well again general criteria and stakeholder goals but until programs using them are further developed impacts remain uncertain.

Acknowledgements

This paper and the underlying research were partly funded by two EC projects:

- Bioenergy, sustainability and trade-offs: Can we avoid deforestation while promoting bioenergy? EuropeAid/ENV/2007/143936/TPS
- Climate Change: Terrestrial Adaptation& Mitigation in Europe (CC-TAME) FP7–ENV-2007-1 Grant #212535

The objective of the first of these projects is to contribute to sustainable bioenergy development that benefits local people in developing countries, minimizes negative impacts on local environments and rural livelihoods, and contributes to global climate change mitigation. The project will achieve this by producing and communicating policy relevant analyses that can inform government, corporate, and civil society decision-making related to bioenergy development and its effects on forests and livelihoods. The project is managed by CIFOR and implemented in collaboration with the Council on Scientific and Industrial Research (South Africa), Joanneum Research (Austria), the Universidad Autónoma de México, and the Stockholm Environment Institute.

CC-TAME's primary objective is to bring land-use modeling to the level of sophistication available in energy modeling and thereby support policy-makers and other stakeholders in evaluations of the impacts, efficiency, and effectiveness of land-use options, including production of biomass for energy. The project will link state-of-the art climate, agricultural soil and yield, forest dynamics, and socio-economic models. The GLOBIUM modeling used within CC-TAME reveal the impact of different accounting approaches on different areas in the world.

Disclaimer

The views expressed herein are those of the authors only. They should in no way be taken to reflect the official opinion of the institutions for which the authors work or organizations with which the authors may be affiliated.

References

Apps M, Karajalainen T, Marland G, Schlamadinger B (1997) Accounting System Considerations: CO_2 Emissions from Forests, Forest Products, and Land-Use Change: a Statement from Edmonton. Availabe at: http://www.ieabioenergy-task38.org/publications/Accounting%20System%20Considerations.pdf (accessed 22 March 2011).

Bird DN, Cowie A, Frieden D *et al*. (2010) *Emissions from bioenergy: improved accounting options and new policy needs*. Proceedings of the 18th European Biomass Conference and Exhibition. Lyon.

Bird DN, Zanchi G, Pena P, Havlík P, Frieden D (2011) *Analysis of the potential of sustainable forest-based bioenergy for climate change mitigation*. Working Paper 59. CIFOR, Bogor, Indonesia. Available at: http://www.cifor.cgiar.org/publications/pdf_files/WPapers/WP59CIFOR.pdf (accessed 15 September 2011).

Cherubini F, Bird DN, Cowie A, Jungmeier G, Schlamadinger B, Woess-Gallasch S (2009) Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. *Resources, Conservation and Recycling*, **53**, 434–447.

Cortez L, Regis M, Leal LV, Sinkala T (2010) Why biofuels are important. In: *Food versus Fuel: an Informed Introduction to Biofuels* (eds Rosillo-Calle F, Johnson FX), pp. 58–85. Zed Books, London.

DeCicco J (2009) *Addressing Biofuel GHG Emissions in the Context of a Fossil-Based Carbon cap*. School of Natural Resources and Environment, University of Michigan, USA. Available at: http://www.snre.umich.edu/sites/snre.umich.edu/files/DeCicco-Biofuels-in-Context-09.pdf (accessed 22 March 2011).

European Union (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. Availbale at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF (accessed 22 March 2011).

Federal Register (2010) Part II. Environmental Protection Agency. 40 CFR Part 80. Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule. 26 March 2010, pp. 14669–15320. Office of the Federal Register, National Archives and Records Administration, Washington, DC.

Havlík P, Schneider UA, Schmid E *et al*. (2011) Global land-use implications of first and second generation biofuel targets. *Energy Policy*, **39**, 5690–5702.

Intergovernmental Panel on Climate Change (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (eds Penman J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Pipatti R *et al*., Hrsg.). The Institute for Global Environmental Strategies for the IPCC and IPCC National Greenhouse Gas Inventories Programme, Hayama, Kanagawa, Japan.

Intergovernmental Panel on Climate Change (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Uses*. Prepared by the National Greenhouse Gas Inventory Programme (eds Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K). IGES, Japan.

Lange M (2011) The GHG balance of biofuels taking into account land use change. *Energy Policy*, **39**, 2373–2385.

Magelli F, Boucher K, Bi HT, Melin S, Bonoli A (2009) An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass and Bioenergy*, **33**, 434–441.

McKechnie J, Colombo S, Chen J, Mabee W, MacLean HL (2011) Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology*, **45**, 789–795.

Peters GP, Marland G, Hertwich EG, Saikku L, Rautiainen A, Kauppi PE (2009) Trade, transport, and sinks extend the carbon dioxide responsibility of countries: an editorial essay. *Climatic Change*, **97**, 379–388.

Pimental D, Marklein A, Toth M *et al*. (2009) Food versus biofuels: environmental and economic costs. *Human Ecology*, **37**, 1–12.

Pingoud K, Cowie A, Bird, DN *et al*. (2010) Bioenergy: counting on incentives. *Science*, **327**, 1199–1200.

Repo A, Tuomi M, Liski J (2011) Indirect carbon dioxide emissions from producing bioenergy from forest harvest residues. *Global Change Biology Bioenergy*, **3**, 107–115.

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

Walker T, Cardellichio P, Colnes A *et al*. (eds) 2010) *Biomass sustainability and carbon policy study: report to the commonwealth of massachusetts department of energy resources*. Report No. NCI-2010-03. Manomet Center for Conservation Sciences, Plymouth, MA, USA. Available at: http://www.manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf (accessed 22 March 2011).

Zanchi G, Pena N, Bird DN (2010) *The upfront carbon debt of bioenergy*. Report for Birdlife International by Joanneum Research. Available at: http://www.birdlife.org/eu/pdfs/Bioenergy_Joanneum_Research.pdf (accessed 22 March 2011).