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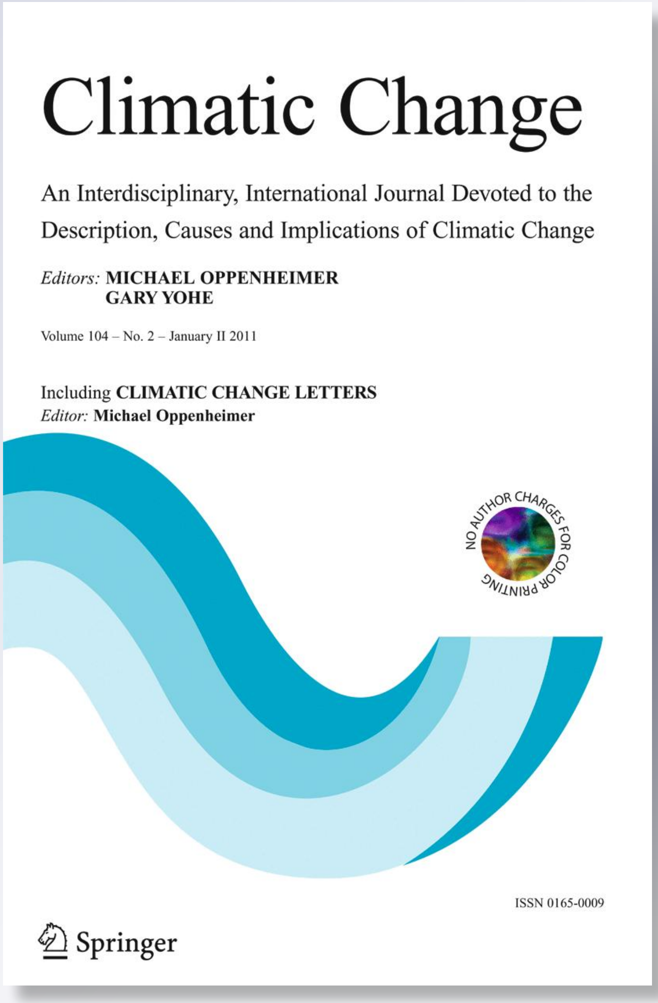

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LETTER

Systematic under- and overestimation of GHG reductions in renewable biomass systems

A Letter

Thea L. Whitman · C. Johannes Lehmann

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Abstract This paper identifies a critical systematic error in greenhouse gas accounting in renewable biomass systems. While CO_2 emissions from renewable biomass energy systems are generally considered to have a net impact of 0, no similar adjustment is made for carbon-based products of incomplete combustion, such as methane, in renewable systems. This results in an under- or overestimation of the impact of CH_4 by 12.3% and CO by ~478% in renewable systems. This error is propagated both in scientific studies and in carbon accounting policies. We advocate first for full-carbon accounting of biomass-derived emissions, but also provide adjusted global warming impacts for emissions from proven renewable systems.

1 Addressing the assumptions of "carbon neutrality"

Current research on and methodologies for biofuel-based carbon accounting perpetuate a systematic error: the misapplication of the concept of "carbon neutrality." While the fact that this concept has been applied inappropriately has been identified (Searchinger et al. 2009), we have noticed an important new error being perpetuated when accounting for the carbon (C)-based non-CO_2 greenhouse gas (GHG) emissions of renewable biomass fuel systems. The crux of the error is that in truly renewable biomass systems, the emission of C-based products of incomplete combustion (PICs), such as methane (CH_4), would result in a lower net GHG impact than under non-renewable conditions (DeLuchi 1991; Varshney and Attri 1999), a fact which is consistently overlooked in C accounting methodologies, resulting in the

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T. L. Whitman (✉) · C. J. Lehmann
College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853, USA
e-mail: TLW59@cornell.edu

under- and overestimation of GHG reductions in systems that rely on renewable biomass for fuel.

At present, the carbon neutral status of biofuels is often justified by the assumption that CO_2 emitted from the combustion of biomass fuels was recently removed from the atmospheric CO_2 stocks by plants fixing C, and thus should not be counted as a net GHG emission (e.g., Roedl 2010). This assumption can be problematic for many reasons (Friedland and Gillingham 2010; Johnson 2009; Pingoud et al. 2010; Searchinger et al. 2009). One of the foremost accounting problems occurs when the removal of biomass from some systems, though it may grow back eventually, actually results in lower net C storage over time than would have occurred under the baseline scenario with no harvesting of biomass (Searchinger 2010). When this is properly accounted for and avoided, we can consider the C in biomass to be truly "additional" (Searchinger 2010). Other sources may use the term "renewable" for this biomass C. We will use this term, because it is consistent with the literature in which the error discussed in this paper is most striking—biomass cook stove literature—but we recognize that "additional" may be a more appropriate term. (We discuss the conditions for the application of this term in more depth in Section 3.)

Carbon accounting for non-CO_2 GHGs has also been problematic. When combustion of fuels is not completely efficient, it produces some carbon-based PICs besides CO_2, such as CH_4, which can have higher global warming impacts than CO_2. While the carbon neutral biofuel paradigm does not count CO_2 from renewable biofuel sources, in some cases, these non-CO_2 gases are counted directly as net GHG emissions (Caserini et al. 2010; Cherubini 2010; Gold Standard 2010; IPCC 2006; UNFCCC 2007). While this is relatively sensible for non-C-based GHGs, such as N_2O, and is an improvement over ignoring all GHG emissions from "renewable" biomass, for C-based GHGs, it is an issue, as we discuss below.

2 The consequences of ignoring C stoichiometry

The best way to understand this error is by considering a system in which completely renewable biomass is combusted. Under perfectly efficient combustion (Supplementary Fig. 1A), each CO_2 molecule released through burning the biomass was originally fixed from atmospheric CO_2 through photosynthesis and will be taken up again as the biomass re-grows, resulting in zero net emissions. The net change in the CO_2 stock in the atmosphere is 0. Under the alternate scenario (Supplementary Fig. 1B), combustion is not perfectly efficient, and some of the C from the CO_2 that was fixed is released upon combustion not as CO_2, but as CH_4. This CH_4 has a warming effect equivalent to 25 times an equivalent mass of CO_2, based on the IPCC's 100-year global warming potential (GWP) (Forster et al. 2007). On a molar basis, rather than the standard mass basis, the warming effect of CH_4 is equivalent to 9.1 times that of CO_2. Under the renewable biomass C neutrality paradigm, we would be inclined to suggest that the net impact of this system is 9.1 mol CO_2-equivalents (CO_2e), because we ignore CO_2 emissions but count all non-CO_2 GHG emissions in a renewable system. However, because CH_4 is a C-based PIC, the emission of one molecule of CH_4 means that one atom of C will not be released as CO_2. If the system is, indeed, renewable, as we have stipulated, then a CO_2 molecule will still be fixed to replace the atom of C released from the plant. Thus, the net impact, or “renewable GWP” (rGWP) of this system is actually $9.1 - 1 = 8.1$ mol CO_2e. Ignoring the biogeochemistry of the system by thinking of “methane gas” and not remembering that this stands for the C-containing chemical compound CH_4, the stoichiometry of the system is lost, and its GHG impact will be overestimated.

The magnitude of this error depends heavily on the GWP of the gases under consideration. Although methane is the only C-based non-CO_2 GHG currently counted under the Kyoto Protocol that would be produced through combustion (HFCs and PFCs contain carbon and are counted, but would not be significant PICs), other PICs are known to have warming effects, such as non-methane hydrocarbons or carbon monoxide (CO), which enhances ozone and reduces OH levels, leading to greater CH_4 concentrations (Forster et al. 2007). For compounds with high GWPs, the overestimation makes only a small difference, but for compounds with low GWPs, it results in a very large error (Fig. 1). For example, in systems where all biomass burning is renewable, the estimated total GHG impact for CH_4 without the renewability correction factor would be 12.3% greater than its true value. If the warming impact of CO, which is estimated to lie around 1.9 by mass (Forster et al. 2007), or 1.2 on a molar basis, is considered, the estimated total GHG impact for CO from renewable sources without the renewability correction factor would be ~478% greater than its true value.

The degree to which this error affects the final estimation of a system's impact scales directly with the fraction of the total system emissions made up by non-CO_2 C-based GHG emissions from renewable biomass. In very clean-burning industrial systems, CH_4 emissions are often relatively low compared to CO_2—the IPCC default CH_4 emission factor for stationary combustion of solid biomass is 0.03% that of CO_2 by mass (IPCC 2006). However, for biomass cook stoves, this ratio may be two to three orders of magnitude higher (Johnson et al. 2008; Smith et al. 1993). In the system studied by Johnson et al. (2008), where 80% of biomass gathering is renewable, the GHG emission reductions achieved through the introduction of improved cook stoves are around 30% higher than they would be if applying the rGWP correction factor. While other uncertainties around the impact of cook stove emissions may be substantial in comparison to this error—for example, the impact

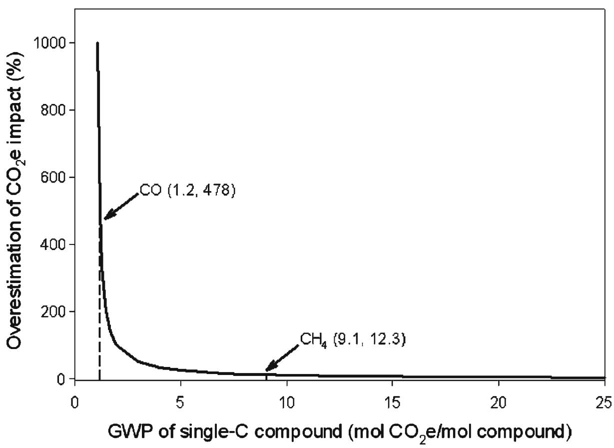

Fig. 1 Percent overestimation of global warming impact vs. molar GWP of single-C GHGs

of particulate black carbon on climate change is poorly understood (Bond and Sun 2005)—this is no excuse to continue to use improper accounting procedures.

It is important to recognize that this error can result in an underestimation or an overestimation of GHG impact, depending on the project scenario and the baseline scenario. Overestimation occurs whenever the project scenario provides a reduction of non-CO_2 C-based GHG emissions from renewable biomass sources from that which was being used under the baseline scenario. An example would be if a cook stove using renewable biomass were improved to require less fuel. However, if the project scenario represents a switch to renewable biomass sources from non-renewable biomass or fossil fuel sources, then this error would cause its potential reductions to be underestimated. For example, if the baseline scenario were fossil fuel burning (all fuel non-renewable) and the project scenario were renewable biomass combustion, then counting uncorrected CH_4 emissions from the biomass combustion would maintain a conservative estimate of emission reductions. If the goal were simply to measure the total emissions of a system, then counting uncorrected CH_4 emissions from the biomass combustion would also result in a higher estimate of total emissions, which would be conservative. In general, an underestimation will result if net emissions from renewable biomass sources increase under the project scenario (although total project emissions may decrease), while a net decrease in emissions from renewable biomass sources results in an overestimation.

3 Righting two wrongs: addressing two carbon accounting issues

Whether this error in accounting for CH_4 and similar PICs is problematic or not depends partially on how CO_2 emissions are accounted for in the first place. We consider here three dominant approaches: (i) CO_2 emissions from biomass fuels are given a GHG impact value of 0, (ii) only a portion of CO_2 emissions from biomass fuels are counted, dependent on what portion of the biomass is from non-renewable sources, (iii) all CO_2 emissions are counted and all changes in biomass C storage over time are also counted. We will not discuss the specific merits or drawbacks of each approach in detail here, but, rather, focus on how the treatment of CO_2 emissions affects the PIC accounting error (as summarized in Table 1).

In the case of the first approach, if it is deemed justifiable to ignore emissions of CO_2, and if CH_4 is considered to be a significant source of emissions (it may not be counted at all (Roedl 2010)), then the same justification for ignoring CO_2 emissions should be applied for using the rGWP or a similar accounting approach for CH_4 emissions. This approach has been used by some (DeLuchi 1991; Sander and Murthy 2010) but is still not applied by others (Caserini et al. 2010; Cherubini 2010; UNFCCC 2007; Gadde et al. 2009). However, as discussed in Section 2, depending on the baseline scenario, this can result in conservative emission reductions (e.g., UNFCCC 2007), in which case it is less critical that the error be righted.

The second approach begins to recognize that in many systems, particularly for wood fuel gathering, biomass comes from different sources with different degrees of renewability. This approach is currently being used in small-scale biomass fuel applications, particularly cook stove research (Johnson et al. 2009; MacCarty et al. 2008), the Kyoto Protocol's Clean Development Mechanism (CDM)'s small-scale methodology (UNFCCC 2009) and the Gold Standard's carbon offset methodology

Table 1 Accounting approaches for CO_2 emissions and C-based non-CO_2 GHG emissions (e.g., CH_4) in biomass fuel systems

Current accounting for CO_2 emissions	Current and recommended accounting for non-CO_2 C-based GHG emissions
CO_2 emissions are given a value of 0 because biomass stocks are determined to be "renewable" or "additional".	C-based non-CO_2 GHG emissions are not included (Roedl 2010) or are included and weighted either using the full GWP (Caserini et al. 2010; Cherubini 2010; Gadde et al. 2009) or the rGWP (DeLuchi 1991; Sander and Murthy 2010). If PIC impacts are included (and CO_2 neutrality is justified), rGWP should be applied, particularly where this results in a conservative estimate of emission reductions.
CO_2 emissions are partly counted (non-renewable biomass) and partly valued at 0 (renewable biomass), depending on fNRB of biomass fuel.	C-based non-CO_2 GHG emissions from non-renewable biomass are included in all cases. Emissions from renewable biomass are excluded (UNFCCC 2009) or included with full GWP weighting (MacCarty et al. 2008; Johnson et al. 2009; Gold Standard 2010) or included with a reduced GWP (Whitman 2010). The impact of PIC emissions from renewable biomass should be weighted using the rGWP, particularly where this results in a conservative estimate of emission reductions.
All C flows within the system are modeled explicitly over time.	The issue of miscounting non-CO_2 C-based GHGs is avoided by modeling the C fixation by plants directly (Bailis 2009; González-García et al. 2010).

for improved cook stoves (Gold Standard 2010). It combines the carbon neutrality paradigm with estimates of the degree of renewability of the biomass used for fuel (Johnson et al. 2010a).

A measure of the fraction of fuel that is from "non-renewable" biomass (fNRB) is used to determine the fraction of CO_2 emissions that should be counted as net emissions, while remaining, "renewable" CO_2 emissions are ignored. In order for this principle to function appropriately, if any biomass designated as "renewable" is gathered from a stock in perpetuity, the stock should both be replenished, and also not have increased beyond its stable level if the gathering were not to have taken place (i.e., be truly "additional" biomass (Searchinger 2010)). If biomass designated as "non-renewable" is gathered from a stock, it should immediately deplete the stock, and the stock should never be replenished. However, these extreme scenarios do not usually apply neatly to a given region, so certain conventions are used to estimate fNRB.

Projects under the CDM consider NRB to be biomass that is not demonstrably renewable and meets at least two out of three other conditions. Demonstrably renewable biomass is defined for forests as cases where: (i) the land area remains a forest, (ii) sustainable management ensures C stocks do not decrease over time, although they may temporarily decrease due to harvesting, (iii) locally applicable forestry and nature conservation regulations are complied with. In addition to not being demonstrably renewable biomass, the three conditions to designate non-renewable biomass are: (i) users spend increasing time or travel increasing distances to gather or transport wood into the project area, (ii) data show that C stocks are being depleted in the project area, (iii) fuel wood price is increasing (UNFCCC 2009).

In these cases where biomass is classified as being renewable or non-renewable, non-CO_2 GHG emissions are not treated consistently. The CDM cook stove approach does not consider any emissions from renewable biomass (UNFCCC 2009), while others consider the non-CO_2 emissions from both renewable and non-renewable biomass sources (Gold Standard 2010; Johnson et al. 2009; MacCarty et al. 2008; Whitman 2010). For non-renewable fuel emissions, CH_4 emissions are weighted by their full GWP and there is no error. However, when renewable fuel emissions are counted, CH_4 emissions should be valued according to the rGWP wherever CO_2 emissions are ignored. The CDM's current methodology remains conservative, because it does not include emissions from any renewable biomass (UNFCCC 2009), but the Gold Standard cook stove methodology and other studies currently overestimate any emission reductions from renewable biomass sources (Gold Standard 2010; Johnson et al. 2008; MacCarty et al. 2008).

Both these first two approaches rely on assumptions about the renewability status of the system. Perhaps the most robust way of addressing such an error is the third approach—to apply full carbon accounting techniques, where the net flows of carbon are explicitly traced over time, including the CO_2 and non-CO_2 emissions from using bioenergy as well as the increases or decreases in net fixation of CO_2 by biological carbon stock due to land-use changes (González-García et al. 2010; Guinée et al. 2009; Johnson 2009; Searchinger et al. 2009). If a biofuel is truly carbon-neutral, then this fact will emanate from the C balance sheet and there is no need to treat CH_4 emissions differently. This system-based solution is an ideal approach for scientific certainty, and can be applied at the project scale by measuring or modelling biomass growth and fuel emissions (Bailis 2009).

4 Fixing the carbon accounting error

Substantially different approaches are being used in order to determine the C budget of renewable biomass fuel systems, with varying consequences. As discussed above, the optimal approach to avoid many C accounting errors and increase confidence in the C accounting for offsets or national inventories would be to use full-system carbon accounting, by explicitly modeling or measuring biomass and soil C growth, decay, and loss as well as emissions.

If renewability status or the fNRB can be justified and are used, however, the proposed rGWP corrections must be applied in place of GWPs for PICs from renewable biomass in order to correct this error (Table 2). (See Shine (2009) for a critique of GWPs and Levasseur et al. (2010) for a discussion of applying GWPs to measure the impacts of gases emitted over time.) To avoid underestimating PIC emission impacts, the rGWP should only be used where biomass can be explicitly proven to be renewable or where applying the correction results in a conservative estimate of emission reductions, such as in improved biomass cook stove systems.

Table 2 One hundred-year global warming potential (GWP) (Forster et al. 2007) and renewable biomass global warming potential (rGWP) on a mass and molar basis

Compound	GWP ($t\ CO_2e/t$ GHG)	rGWP ($t\ CO_2e/t$ GHG)	GWP (mol CO_2e/mol GHG)	rGWP (mol CO_2e/mol GHG)
CH_4	25	22.26	9.12	8.12
CO	1.9	0.33	1.21	0.21

This recommendation should be added to those discussed by Johnson et al. (2010a, b) for revising the current accounting procedures for biomass cook stove systems, and to those recommended by Searchinger et al. (2009) for improving GHG inventories.

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