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Climate impacts of bioenergy: Inclusion of carbon cycle and albedo dynamics in life cycle impact assessment

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ABSTRACT

Life cycle assessment (LCA) can be an invaluable tool for the structured environmental impact assessment of bioenergy product systems. However, the methodology's static temporal and spatial scope combined with its restriction to emission-based metrics in life cycle impact assessment (LCIA) inhibits its effectiveness at assessing climate change impacts that stem from dynamic land surface–atmosphere interactions inherent to all biomass-based product systems. In this paper, we focus on two dynamic issues related to anthropogenic land use that can significantly influence the climate impacts of bioenergy systems: i) temporary changes to the terrestrial carbon cycle; and ii) temporary changes in land surface albedo—and illustrate how they can be integrated within the LCA framework.

In the context of active land use management for bioenergy, we discuss these dynamics and their relevancy and outline the methodological steps that would be required to derive case-specific biogenic CO_2 and albedo change characterization factors for inclusion in LCIA. We demonstrate our concepts and metrics with application to a case study of transportation biofuel sourced from managed boreal forest biomass in northern Europe. We derive GWP indices for three land management cases of varying site productivities to illustrate the importance and need to consider case- or region-specific characterization factors for bioenergy product systems. Uncertainties and limitations of the proposed metrics are discussed.

1. Introduction

Life cycle assessment (LCA) is an analytical tool widely used today in regulatory proposals to set environmental and climate performance criteria and standards for bioenergy and biofuels (Bringezu et al., 2009). In contrast to national accounting frameworks, value-chain approaches like LCA account for greenhouse gas (GHG) emissions along a series of processing steps – from biomass cultivation, transportation, conversion to final bioenergy product, end use, etc. – for purposes of attributing them to the bioenergy product system. It is often applied in decision analysis at a single product, or "micro" analysis level (Hofstetter, 1998; Hofstetter et al., 2002). A notable feature of LCA's analytical framework is its indifference to the time dimension with respect to environmental impact assessment. In other words, LCA essentially treats past, present, and future emission interventions equally and integrates them over time, and environmental impacts, irrespective of the moment that they occur, are equally included (Hellweg et al., 2003; Udo de Haes et al., 1999). For CO_2 fluxes in biomass systems, this methodological aspect has serious implications. For example, the warming impact that occurs from CO_2 emissions from biomass conversion or combustion is often neglected because it is assumed that the quantity of CO_2 assimilated during growth will approximately equal that which is released upon being oxidized ("carbon and climate neutrality" principle). This practice is so widespread in biofuel LCA application that, out of 67 studies[1] evaluated in a recent biofuel LCA review study performed by van der Voet et al. (2010), 63 failed to even state this assumption. A less widespread convention in LCA of bioenergy (2 out of 67 in van der Voet et al., 2010) has been to explicitly account for the biogenic CO_2 intervention at each life cycle stage; in other words, as negative emissions during biomass growth and positive emissions during biomass combustion—an inventory modeling approach adopted by some circles (Ecoinvent, 2009; Rabl et al., 2007). While the assumption that carbon neutrality equals climate neutrality may be reasonable when the bioenergy product is derived from fast growing biomass feedstocks (i.e., annuals), it becomes questionable for bioenergy derived from slower growing feedstocks (i.e., SRC, forest biomass). A forest may take about 100 years to re-grow, and the amount of CO_2 released at one point in time for bioenergy equals the amount of CO_2 sequestered in the new vegetation only at the end of this timeframe. Therefore, the system requires several decades to be carbon neutral, and the equivalency between the concepts of carbon neutrality and climate neutrality can no longer

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[1] Including Bright and Strømman (2009).

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applied. The temporal issue surrounding a biogenic CO_2 emission and its climate impact has been sufficiently dealt with by researchers in other disciplines that utilize different modeling frameworks (see for example Marland and Marland, 1992; Schlamadinger and Marland, 1996a,b; Schlamadinger et al., 1997), but until recently, a proper treatment of the time dimension in life cycle impact assessment (LCIA) of biogenic CO_2 emission has been missing.

Another limitation of LCA when it comes to the climate impact assessment of bioenergy is the tool's reliance on emission-based metrics like global warming potential (GWP). With regards to land use, biogeo*physical* factors such as changes in surface reflectivity (albedo), evaporation/transpiration, and surface roughness play an important role in regulating surface energy fluxes and the hydrologic cycle—both affecting climate across various temporal and spatial scales (Betts, 2007; Bonan, 2008; Jackson et al., 2008; Marland et al., 2003; Pielke Sr. et al., 2002). For example, when including biogeophysical factors resulting from hypothetical conversion of annual to perennial crops for bioenergy in the U.S., Georgescu et al. (2011) simulate a strong cooling effect related to local increases in transpiration and higher surface albedo, with the albedo cooling effect alone being six times larger than the annual biogeochemical effects that arise from offsetting fossil fuel use. Similarly, Loarie et al. (2011) report that expanding sugar cane production into existing crop and pasture land in Brazil enhanced albedo and increased evapotranspiration, cooling climate locally relative to the former cropland/pasture. Thus, when it comes to the influence of land use and land surface–atmosphere dynamics on the climate system, biogeophysical factors play an important role and are equally as relevant to climate policy as the effects from changes in GHG emission.

Radiative forcing, or the perturbation to the global radiation budget prior to any feedbacks resulting from the response of other aspects of the climate system (Forster et al., 2007), is a metric that can be used to compare the effects of changes in some biogeophysical parameters, like changes to surface albedo, with the effects of changes in GHG emissions. For bioenergy systems, a radiative forcing is induced when the albedo value of the land surface changes when a biomass feedstock is either planted or harvested. Radiative forcing, however, cannot be used to quantify all mechanisms of a climatic perturbation like those acting directly via surface moisture fluxes (Betts et al., 2007; Pielke Sr. et al., 2002). For example, a change in the partitioning of available energy into latent and sensible heat fluxes (Bowen ratio) due to a change in evaporation or transpiration does exert a climate forcing by impacting near-surface air temperatures but cannot be compared with the concept of radiative forcing (Pielke Sr. et al., 2002). Nevertheless, the albedo effect is the dominant biogeophysical effect on the global scale (Betts, 2001), and radiative forcing from albedo changes can be integrated within the life cycle impact assessment (LCIA) framework for comparing with radiative forcings from emissions.

1.1. Objectives

In this paper, our primary objective is to illustrate how carbon cycle and albedo dynamics can be incorporated in life cycle impact assessment (LCIA). We first discuss the importance of considering atmosphere–biosphere CO_2 flux *timing* when modeling the carbon cycle radiative forcing impacts of bioenergy product systems in the absence of permanent land use change. We elaborate on the recent work of Cherubini et al. (2011a) by showing how the "GWP_{bio}" index of characterization factors can be tailored to specific LCA case study applications. GWP_{bio} is based on a characterization model that is considerate of the effective sink capacity of a biomass feedstock and the radiative forcing impacts of a biogenic CO_2 emission in time. CO_2 sequestration and emission fluxes are essentially linked in time for attributing a forcing impact to the bioenergy product system using a single factor. We focus here on a single case – transportation biofuel produced from slow growing forest biomass in Norway – and test the influence of three different growth rates as it affects the atmospheric CO_2 concentration time profile influencing the derived GWP_{bio} characterization factors.

Secondly, we illustrate how radiative forcing impacts from surface albedo changes associated with land use occupation can be included in LCIA of bioenergy[2] product systems when surface albedo evolves in time due to biomass re-growth following harvest for bioenergy (i.e., when the initial surface albedo perturbation no longer results in a radiative forcing). We outline the steps required to derive a "GWP_{albedo}" characterization factor that is inclusive of this dynamic and apply our concepts to the same case study.

2. Inclusion of dynamic biogenic CO_2 fluxes in life cycle impact assessment

According to the methodological aspects of LCA described above, the accounting of biogenic CO_2 in bioenergy systems generally follows the standard conventions regarding no-preference for time (zero discount rate) in LCA, and therefore they usually bypass the temporal issue of time discrepancy between CO_2 emissions (through combustion or oxidation) and removals (through vegetation growth). Neglecting such a time dimension may be questioned if specific time boundaries are set (either to address requests from policy makers or impact category indicators, as GWP). Cherubini and co-authors recently proposed an approach to overcome this limitation by integrating the biogenic CO_2 fluxes in biomass systems within the global carbon cycle (Cherubini et al., 2011, in press). This methodology overcomes the de facto assumption that carbon neutrality equals climate neutrality by considering that all CO_2 emissions and removals cause a perturbation to the CO_2 atmospheric concentration, thereby causing a climate impact which cannot be neglected. The change in atmospheric CO_2 concentration is modeled by means of Impulse Response Functions (IRF), which describe the perturbation of a dynamic system caused by some external change. Among the existing IRFs, the IRF from the Bern 2.5CC model is here used to predict the atmospheric decay of anthropogenic CO_2, $y_{CO2}(t)$. This function represents the fraction of CO_2 remaining in the atmosphere after a single pulse emission depending on the interactions between the atmosphere, the oceans, and the terrestrial biosphere (Joos, 1996; Joos et al., 2001).

This IRF $y_{CO_2}(t)$ has the following analytical form (Forster et al., 2007):

$$y_{CO_2}(t) = A_0 + \sum_{i=1}^{3} A_i e^{-t/\beta_i} \quad (1)$$

where $A_0 = 0.217$, $A_1 = 0.259$, $A_2 = 0.338$, $A_3 = 0.186$, $\beta_1 = 172.9$, $\beta_2 = 18.51$, $\beta_3 = 1.186$.

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 β_i.

The time-distributed emissions and removals of CO_2 from biomass systems are a perturbation of this dynamic system, and their combination with the IRF for anthropogenic CO_2 provides the corresponding change in CO_2 atmospheric concentration. In mathematical terms, this is implemented with a convolution between the emission and removal functions with the CO_2 decay from the air:

$$f_{CO_2}(t) = \int_0^t \left[C_0 \delta\left(t'\right) - C_0^* g\left(t'\right)\right] y_{CO_2}\left(t - t'\right) dt' \quad (2)$$

[2] Here we focus on bioenergy product systems. Our approach may be applied to any type of agricultural product system.