Development of life cycle assessment for residue-based bioenergy

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Chapter 4

Effect of biogenic carbon inventory on the life cycle assessment of bioenergy

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Abstract

Biogenic carbon is defined as carbon contained in biomass that is accumulated during plant growth. In spite of considerable progress towards the inventory of biogenic carbon in the life cycle assessment (LCA) of bioenergy in policy guidelines, many scientific articles tend to give no consideration to biogenic carbon, due to the neutrality assumption, rather than employing a complete inventory according to the LCA principles. Meanwhile, the assumption of biogenic carbon neutrality has been previously challenged on the basis of changes in soil carbon stock due to land use change and carbon storage capacities of long-rotation trees or wood products. Supporting this argument, we investigate three other inventory aspects, namely, differences in framing system boundaries (cradle to grave vs. cradle to gate), forms of carbon emissions (carbon dioxide vs. methane), and valuation of biogenic carbon (biomass products vs. biomass residues). Referring to a generic bioenergy system, our analysis is focused on eight scenarios of various carbon flows encompassing biomass decomposition in fields and its alternative utilization as bioenergy feedstocks. These scenarios are applicable to both biomass products and biomass residues, which impacts proportionally depend on the chosen allocation criteria between the two. Further, a framework to quantify the performances of the various carbon flows on global warming impacts is formulated. The operation of the framework demonstrates that the assumption of biogenic carbon neutrality introduces a bias to the ‘true’ values based on a complete inventory. This can make the values of global warming impacts substantially higher or lower when different system boundaries, forms of carbon emissions, and biomass valuation are taken into account. The results of this study are expected to contribute to the harmonization of future bioenergy LCA by directing further research to adopt more the concept of utilizing a complete inventory rather than the neutrality assumption.

Keywords
Biogenic carbon neutrality, Biomass residues, Biomass valuation, Global warming impact, Life cycle inventory, System boundary.

4.1 Introduction

Biogenic carbon is defined as carbon contained in biomass that is accumulated during plant growth involving photosynthetic processes. Variations in the inventory of biogenic carbon can be easily ascertained in life cycle assessment (LCA) practices. Downie et al. (2014), for example, has recently discussed various approaches to greenhouse gas (GHG) accounting for biogenic carbon. These different inventory approaches often incite confusion in interpretation due to their divergent final results. In addition, many LCA studies concerning bioenergy tend to give no consideration to biogenic carbon, due to carbon neutrality assumptions, rather than employing a complete inventory. The reason behind the neutrality assumption is that biogenic carbon sequestered during growth is believed to be released back in the same amount and forms, either naturally decomposed or burned, so that there is no net increase in the atmospheric GHGs. One recent example is an article published by Liska et al. (2014) regarding the estimation of CO_2 emissions from crop residue-derived biofuels. The article has stimulated scientific debates and thus has received several reactions, one of which is the critique of omitting biogenic carbon from the inventory (Bentsen et al., 2014). In this regard, it is important to identify which approaches are more accurate than others for a certain situation. Theoretically, any deviations when performing an inventory from the LCA principles, i.e., treating all relevant input-outputs as genuine flows including biogenic carbon, would move the final scores away from the true values. Moreover, it would be biased if such deviating results are for example exploited for policy making such as in taxes or incentives applied to bioenergy products.

The objective of this study is to examine the consequences of applying carbon neutrality assumptions (excluding biogenic carbon from an inventory) in the LCA of bioenergy systems whereby the analysis is focused on the global warming impact at different system boundaries (cradle to grave vs. cradle to gate), forms of carbon emissions (CO_2 vs. CH_4), and valuation of biogenic carbon (biomass products vs. biomass residues). In doing so, this study proposes a method to quantify global warming performances of various possible carbon flows in a generic bioenergy system based on a life cycle approach. These carbon flows encompass decomposition of biomass in fields and its alternative utilization as bioenergy feedstocks.

The remainder of the article is structured in the following manner. Section 2 describes the problems of inconsistencies in biogenic carbon inventories in policy guidelines and scientific literature, challenges to the biogenic carbon neutrality assumption, and inventory aspects in terms of system boundaries, forms of carbon emissions, and biomass valuation. Section 3 describes a step-by-step method for assessing global warming impacts of various carbon inventory scenarios. Finally, Section 4 discusses the results and their implications on the assumption of biogenic carbon neutrality.

4.2 In-depth description of the problems

4.2.1 Biogenic carbon inventory in policy guidelines and scientific literature

There is still debate regarding the manner to treat biogenic carbon in bioenergy systems in a policy context. At the global level, the Intergovernmental Panel on Climate Change (IPCC) adopts a carbon stock method rather than an input-output flow approach in accounting for biogenic carbon (Levasseur et al., 2013). A similar approach is also employed by the United Nations Framework Convention on Climate Change (UNFCCC) in order to report country's emissions resulting from land use and energy as separate sectors (Haberl et al., 2012). Encompassed within these frameworks, if trees are cleared from forest and, later in the life cycle, the biomass is combusted as bioenergy, the carbon that is lost from combustion can alternatively be expressed as a land use change (LUC). Consequently, in this case, the CO_2 emissions from biomass combustion will no longer be considered to avoid double counting, i.e., the emissions from biomass combustion are considered as zero. This latter argument is often utilized inaccurately as a basis to assume biogenic carbon neutrality. In contrast, Haberl et al. (2012) clearly stated that the above accounting practices do not justify biogenic carbon neutrality but, instead, provide an option that emissions generated from biomass combustion can optionally be inventoried as LUC. If done properly, either ways (claims as combustion or land-use emissions) would lead to the same results. More precisely, the authors stated that "the assumption that all biomass is carbon-neutral results from a misapplication of the original guidance provided for the national-level carbon accounting under the UNFCCC". We think that such an observation could be derived easily since Haberl and coworkers observed the entire bioenergy system from the life cycle perspective. This approach is based on the recognition that a complete inventory will provide a more accurate estimate of carbon balances. The current article adopts this view to establish criteria to examine the assumption of biogenic carbon neutrality in bioenergy systems.

The carbon accounting based on the carbon stock method would essentially result in the correct results if applied consistently, i.e., carbon emissions are all expressed either as land use or as energy use. Considering this, not-inventorying the emissions from biomass-use as bioenergy do not imply that the biomass is automatically 'carbon neutral'. The following is an example of possible inconsistency when applying the carbon stock method. The coverage of the UNFCCC accounting system for global warming is applicable to all countries worldwide. Meanwhile, Kyoto Protocol caps emissions from land use and from energy sectors differently for Annex 1 and non-Annex 1 parties, primarily consist of developed and developing countries, respectively (Haberl et al., 2012; UNFCCC, 2014). The first authors further stated that the protocol potentially caused errors as a consequence of the non-homogenous implementation of the accounting rules in different countries. In this regard, incomplete information regarding the inventory during an initial phase (LUC) could result in double counting or GHG emissions never being accounted for at all.

In spite of some progress towards the inventory of biogenic carbon in the life cycle assessment (LCA) of bioenergy, variations can still be ascertained between policy guidelines. As discussed in Johnson (2009), a life-cycle based method such as the British PAS 2050 initially did not consider biogenic carbon uptakes and emissions. Subsequently, its revised version clearly states that all biogenic carbon flows must be considered (BSI, 2011). The same applies for the GHG protocol developed by World Resources Institute and World Business Council for Sustainable Development (WRI-WBCSD, 2011). Similarly, the International Reference Life Cycle Data System (EC-JRC-IES, 2010) that was developed by the European Commission recommended the use of LCA principles with a complete input-output flow approach. Meanwhile, EU (2009) expressed carbon neutrality in a slightly different manner, where the capture of CO_2 in the cultivation of biomass and emissions from biofuel use were valued as zero.

Divergence in ways to develop biogenic carbon inventories is more extensively found in the scientific literature of bioenergy LCA. Based on a survey that exceeded 100 publications, most solid bioenergy studies disregarded biogenic carbon emissions in the combustion of biomass (Johnson, 2009). More specifically, out of the 25 researchers working on the GHG emissions of wood fuel, only one group did not assume biomass to be carbon neutral. Similarly, nearly half of the liquid biofuel studies did not include biogenic carbon in their inventory (Wiloso et al., 2012). In this survey, 13 out of 27 LCA studies of second generation bioethanol based on energy crops and biomass residues did not consider carbon sequestration through photosynthesis. This indicates that the attitude towards adopting the concept of biogenic carbon neutrality varies between LCA studies, i.e., 96% for solid bioenergy and 48 % for second-generation liquid biofuel. This is quite a surprising observation that many scientific articles tend to give no consideration to biogenic carbon considering the neutrality assumption, which admittance varies depending on the forms of bioenergy (solid vs. liquid). In accordance with the trend in the policy guidelines, perhaps, additional scientific publications in the future would adopt more the concept of utilizing complete inventory rather than assuming carbon neutrality. This paper intends to contribute to the harmonization of the LCA of bioenergy in favor of the above perspective.

4.2.2 Challenges to the assumption of biogenic carbon neutrality

According to the LCA principles, carbon uptake from the atmosphere should be incorporated into the inventory like all other relevant emission flows. Therefore, biogenic carbon can be regarded as carbon neutral when the net global warming scores are zero, which is an ideal condition where flows between carbon capture (photosynthesis) and carbon emissions (natural decomposition) are balanced. Based on the neutrality assumption, these two natural processes are traditionally excluded from the inventory with the belief that this would not affect the final results. However, there is an additional requirement in order for this scenario to be valid. The new growing trees must replace the biomass that was previously harvested in relatively short term, i.e., fast growing trees, as opposed to slow-growing trees like forests (Cherubini et al., 2011; Guest et al., 2013). Annual crops for example are encompassed within the category of fast-growing trees. In this case, the decayed woody biomass could simply be a component of the short-lived carbon cycle which does not increase the amount of atmospheric carbon due to compensation by, relatively, the un-delayed photosynthetic processes.

In contrast to the natural process of biomass decomposition, bioenergy systems typically involve an increasingly complex, greater number of input-output flows. Along the life cycle, fossil fuel is incorporated in substantial amounts in both the agricultural and bioenergy conversion phases. The subsequent disturbed carbon balance will typically result in a non-zero global warming score. From an LCA perspective, the bioenergy systems can be perceived as not carbon-neutral due to the net increase in GHG emissions. Such a conclusion however cannot be observed easily when employing the previously discussed carbon stock method. This indicates that a life cycle approach is more suitable as a tool for examining the carbon neutrality assumption of a bioenergy system.

Certain other factors have been recognized as potentially disturbing the above carbon balance even more, serving as an argument often used to question the concept of carbon neutrality (Rabl et al., 2007; Johnson, 2009). The most important one is the effect of land use and LUC on soil carbon stock (Searchinger et al., 2008). This is often the case since biomass or bioenergy systems typically involve agricultural activities entailing intensive carbon exchange among trees, soil, and the atmosphere. It has been concluded that the production of food-crop-based biofuels may create a carbon debt, i.e., a situation where GHGs released from soil are much more substantial than the annual GHG savings from biofuels substituting fossil fuels.

Another influencing factor concerns the temporal aspects that delay carbon emissions into the atmosphere which relates to the temporary carbon-storage capacity of wood products. To address this time frame issue, Levasseur et al. (2013) proposed treating biogenic carbon with dynamic LCA. It is considerably appropriate for describing the environmental performance of, for example, long-storage wood-based products such as furniture. The argument in support of this approach is that, during the use-phase of a product, the concentration of CO_2 in the atmosphere is temporarily decreased and some radiative forcing is avoided (Levasseur et al., 2012). The primary features of this dynamic LCA are the utilization of dynamic inventory and dynamic characterization factors. A similar contribution was also initiated by Cherubini et al. (2011) who developed a characterization factor of biogenic global warming potential (GWPbio) for bioenergy based on various types of energy crops. The GWPbio ranging from 0 to 1 characterizes the climate change effects of biogenic carbon relative to fossil carbon. This concept is appropriate for describing the bioenergy systems based on biomass feedstock of different degrees of renewability, for example, annual crops versus boreal-forest of a more than 100 year rotation period. The GWPbio considers two related parameters including carbon sequestration in biomass and CO_2 decay in the atmosphere.

To support the idea of applying complete inventory in the LCA of bioenergy, including biogenic carbon, the current paper evaluates three relevant inventory aspects. They are differences in framing system boundaries (cradle to grave vs. cradle to gate), forms of carbon emissions (CO_2 vs. CH_4), and valuation of biogenic carbon (biomass products vs. biomass residues). Integrative discussion regarding these three aspects with regard to the assumption of biogenic carbon neutrality in the literature has, thus far, been lacking, but will be elaborated further in the following sections.

4.2.3 Coverage of system boundaries

To acquire the true value according to the LCA principles, ideally, an analysis ought to be carried out on a complete life cycle system boundary. However, in practice, many processes are left out for different reasons, for example, constraint in terms of time and money. In this regard, a cradle-to-gate approach often can be sufficient for comparing options to make the same bioenergy from different feedstocks (biomass products vs. residues; biomass from LUC vs. land use phases). It is performed by excluding the use and final-disposal stages, but it is, of course, admissible only when there is no difference within these stages between the compared options. However, the presence of biogenic carbon at the agricultural phase and at end of life cycle in some cases adds layer of complication. Options to include or exclude the biogenic carbon could affect the quantification of global warming impacts, particularly, if the calculation is made at different system boundaries. The varying final results require a clear interpretation. To further examine this effect, this study quantifies the global warming impacts of bioenergy on the basis of different system boundaries (cradle-to-gate vs. cradle-to-grave).

4.2.4 Forms of carbon emissions

Theoretically, the most appropriate way to treat carbon cycles is to consider them as genuine cycles. All possible carbon pathways of captured and emitted carbon species such as CO_2, CH_4, and CO should be, ideally, considered in the inventory. For example, during tree growth, a certain amount of atmospheric CO_2 is fixed and ultimately released as CO_2. However, it is not always the case. Some of the carbon may be released back to the atmosphere not in the same form but, rather, as CH_4 or CO. The latter is a by-product of an incomplete combustion. Having GWP100 in the range of 2 to 5, CO is relatively short-lived in the atmosphere and easily transformed into other forms (IPCC, 2013). For this reason, CO is not discussed any further here. Meanwhile, CH_4 is a well known, important GHG having a much more substantial GWP100, 34 times higher than CO_2 (IPCC, 2013). The formation of CH_4 in bioenergy systems may occur, for instance, when the biogenic carbon is subject to anaerobic decomposition with leakages occurring along the way. The analysis on the effect of CH_4 emissions on global warming has recently been reported by Whitman and Lehmann

(2011). The current paper attempts to address the same issues in connection with other relevant aspects in bioenergy systems such as biomass valuation and system boundary.

This paper focuses on the discussion on the inventory of carbon emissions only. It is more a carbon accounting at the inventory level rather than a complete global warming assessment which is typically to include also non-carbon emissions such as nitrous oxide (N_2O) or hydro fluorocarbons (HFCs). However, since it is presupposed that these non-carbon emissions are constant for all developed scenarios, omitting the non-carbon GHG emissions in the inventory would not affect the outcome of the comparative analysis (including or excluding biogenic carbon), which is the main objective of the study. Subsequently, we will restrict the inventory to a narrow definition of GHG emissions comprising only CO_2 and CH_4. This principle is further adopted in the methodology section to demonstrate how different forms of carbon emissions affect final results. Accordingly, the results of this study should be viewed from the perspective of accounting carbon flows only. For complete global warming assessment, the other relevant GHG species should be evaluated as well.

4.2.5 Valuation of biomass

A large number of studies on the LCA of bioenergy have not clearly defined the economic status of biomass residues. This is an important issue since bioenergy feedstocks in general can be derived from biomass products (food products, energy crops) or biomass residues. In this paper, biomass residues are referred to as non-edible portions of plants generated in fields. To avoid complexity, those generated at post-harvest processing plants are not discussed here. Biomass residues are not intentionally produced for certain purposes, instead, as co-products of a specific product system (for example, food, feed, or fibers). While biomass products are obviously goods, biomass residues can be regarded either as goods or as waste depending on the nature of the situation. Unless specifically mentioned, in this paper, the term 'biomass' refers to either biomass products or residues. The bioenergy system is formulated in generic forms, thus, applicable to both biomass products and biomass residues.

It is particularly important to elucidate how the valuation schemes for biomass would actually affect final LCA results. In LCA, economic flows travel between two unit processes whereby each economic flow must be the output of one process or the input of another process (Heijungs and Frischknecht, 1998). Additionally, the flow can be regarded as goods if it possesses a positive economic value, whereas waste features a negative economic value (Guinée et al., 2009). These criteria can be further utilized as a basis to appropriately allocate environmental burdens to flows of different economic status. A waste stream in LCA is conventionally assumed to be free of environmental burden (Wiloso et al., 2015). The impact of this stream is allocated entirely to the sub-system preceding the waste stream. In contrast, if a flow is goods, the preceding streams will be automatically included in the inventory of the entire product system. Such a procedure is of particular importance considering the increasing trend of utilizing biomass residues as bioenergy feedstock. These principles are further adopted in the methodology section in order to examine how biomass valuation can affect final LCA results. Accordingly, the impacts of bioenergy derived from biomass products and residues are considered based on partitioning methods (allocation criteria), i.e., relative valuation between the two biomass. This aspect has been discussed thoroughly in the previous paper (Guinée et al., 2009). To avoid complexity, other ways of treating multi-functional issues in LCA, such as system expansion, is not considered in this current paper.

4.3 Methods

To illustrate how a global warming impact at various biogenic carbon inventories are calculated, a generic bioenergy system was created as exhibited in Figure 4.1. Within the system boundary, different sources of biomass feedstocks (biomass products or residues, from LUC or land use phases) and related carbon flows were identified. Biomass residues are either naturally decomposed when left in fields or removed and converted into bioenergy. Meanwhile biomass products will be used only as bioenergy feedstocks. Several biogenic carbon inventory scenarios were developed encompassing the most relevant biomass utilization routes, i.e., naturally decayed or converted into bioenergy. The inventory considered relevant carbon flows of the entire life cycle of the bioenergy system. The models were developed in such a way that it can simulate the above processes (decomposed or converted into bioenergy) as comprehensively as possible. Each types of carbon flows (soil, fossil, and biogenic carbons) were explicitly presented to allow for proper accounting. The analysis was focused on three major inventory issues, i.e., coverage of system boundaries (cradle to gate or cradle to grave), forms of carbon emissions (CO_2 or CH_4), and valuation of biogenic carbon (biomass products or residues).

Within the system boundary, bioenergy feedstocks were differentiated as biomass products or biomass residues, which contributions to the overall impacts depend on the chosen allocation criteria between the two. Accordingly, all biomass products are valued as goods while biomass residues are valued as either goods or waste. In this regard, biomass residues were not only generated in fields but also at post-harvest processing plants. For simplicity, the latter cases (biomass residues as waste and generated at post-harvest processing plants) are not discussed any further here.

The study was designed to compare the global warming performances in cases where biomass residues were naturally decomposed in fields (in hypothetically perfect aerobic or perfect anaerobic conditions) or where biomass products or residues was removed from fields, converted into bioenergy, and finally used (combusted). To that end, relevant inventories were consequently developed as exhibited in Table 4.1. In cases where biomass residues are naturally decomposed, it was assumed that all carbons emitted from biomass residues were either in the form of CO_2 (as a result of perfect aerobic decomposition or perfect burning) or all in the form of CH_4 (as a result of perfect anaerobic decomposition such as being disposed of into an enormous pile or land filled). Table 4.1 also lists the various carbon inventories of cases where biomass products or residues are removed from the fields, converted into bioenergy, and subsequently used. Different from the decomposition cases, all carbons emitted within the bioenergy system were assumed in the form of CO_2.

As indicated in the last two columns in Table 4.1, the procedure to quantify global warming impacts is divided into two categories, i.e., including biogenic carbon (the preferred approaches) and excluding biogenic carbon (the biogenic carbon neutral assumption). Results of these different approaches will be compared in order to examine how the neutrality assumptions would move results away from the complete inventory.

The hypothetical inventory data comprising relevant carbon capture and emissions are provided in Table 4.2. The explanation for utilizing hypothetical data was due to the fact that inventory datasets for actual situations are not typically available with such levels of comprehension, i.e., differentiating carbon flows (soil, fossil, and biogenic carbons), modes of decomposition (aerobic and anaerobic), and biomass valuation (products and residues). Except for soil emissions and biomass decomposition, all other positive emissions indicated in the table are introduced by input fossil fuels within the system boundary (LUC, LU, bioenergy production and use phases).

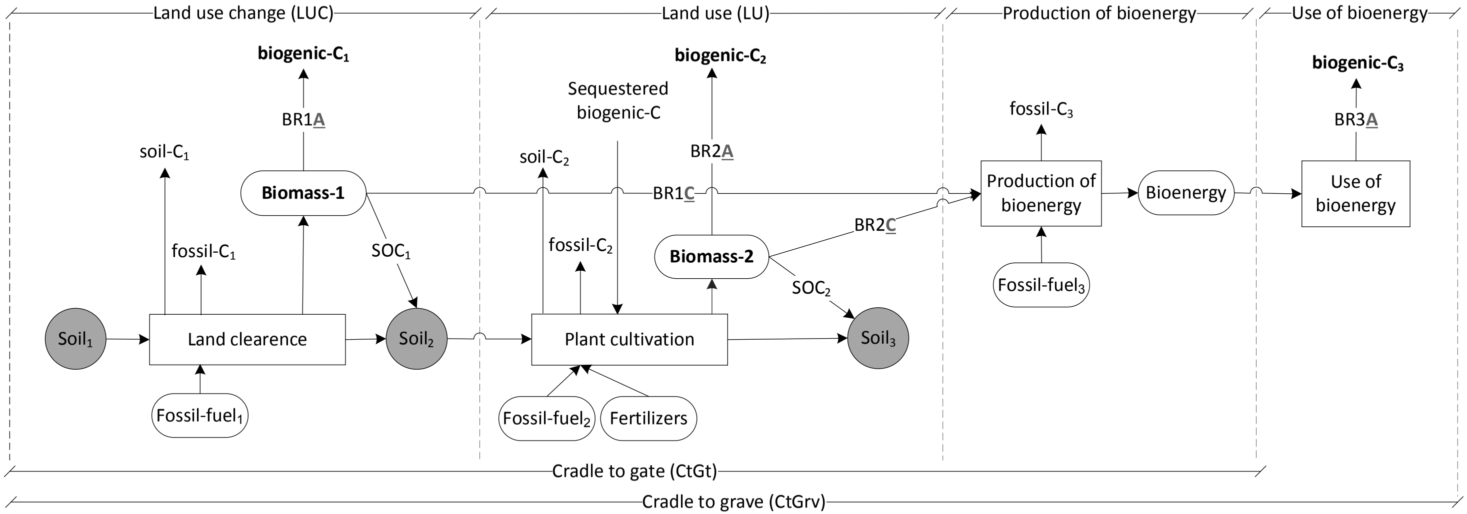

Figure 4.1. System definition of biomass-residue decomposition and alternative carbon flows as bioenergy feedstocks.

This is a generic bioenergy system, applicable to biomass products and residues. Biomass residues are either naturally decomposed in fields or removed and converted into bioenergy, while biomass products will only be used as bioenergy feedstocks. Not all of the carbon from the decomposed biomass is emitted as biogenic carbon (BR1A and BR2A), some fractions would be recycled back as soil organic carbon (SOC_1 and SOC_2). Bioenergy feedstocks can be derived from biomass products or residues generated at LUC (BR1C) or LU (BR2C) phases. ▭ = anthropogenic processes; ⬭ = economic flows (biomass residues, fossil fuels, fertilizers, and bioenergy); text without structures = environmental flows (soil-C, fossil-C, and biogenic-C). CtGt is a boundary for bioenergy at the gate of production facilities, while CtGrv is a complete bioenergy life cycle boundary, including the use phase.

Table 4.1. Procedures to quantify global warming performances of various carbon flows in bioenergy systems [a].

<table>
<tr><th rowspan="2">Biomass residues decomposed in fields</th><th rowspan="2">Codes</th><th colspan="4">CO_2-equivalent (kg)</th></tr>
<tr><th colspan="2">Excluding biogenic carbon (carbon neutral)</th><th colspan="2">Including biogenic carbon (preferred approaches)</th></tr>
<tr><td>At a LUC phase, emitted as CO_2</td><td>BR1A-CO_2</td><td colspan="2">soil-C_1+
fossil-C_1</td><td colspan="2">soil-C_1+
fossil-C_1+
biogenic-C_1 as CO_2+
biogenic-C_1 as SOC_1</td></tr>
<tr><td>At a LUC phase, emitted as CH_4</td><td>BR1A-CH_4</td><td colspan="2">soil-C_1+
fossil-C_1</td><td colspan="2">soil-C_1+
fossil-C_1+
biogenic-C_1 as CH_4+
biogenic-C_1 as SOC_1</td></tr>
<tr><td>At a LU phase, emitted as CO_2</td><td>BR2A-CO_2</td><td colspan="2">soil-C_2+
fossil-C_2</td><td colspan="2">soil-C_2+
fossil-C_2+
sequestered biogenic-C+
biogenic-C_2 as CO_2+
biogenic-C_2 as SOC_2</td></tr>
<tr><td>At a LU phase, emitted as CH_4</td><td>BR2A-CH_4</td><td colspan="2">soil-C_2+
fossil-C_2</td><td colspan="2">soil-C_2+
fossil-C_2+
sequestered biogenic-C+
biogenic-C_2 as CH_4+
biogenic-C_2 as SOC_2</td></tr>
<tr><th colspan="2">Biomass products or residues converted into bioenergy</th><th>CtGt</th><th>CtGrv</th><th>CtGt</th><th>CtGrv</th></tr>
<tr><td>From a LUC phase</td><td>BR1C</td><td>soil-C_1+
fossil-C_1+
fossil-C_3</td><td>soil-C_1+
fossil-C_1+
fossil-C_3</td><td>soil-C_1+
fossil-C_1+
fossil-C_3</td><td>soil-C_1+
fossil-C_1+
fossil-C_3+
biogenic-C_3, CO_2</td></tr>
<tr><td>From a LU phase</td><td>BR2C</td><td>soil-C_2+
fossil-C_2+
fossil-C_3</td><td>soil-C_2+
fossil-C_2+
fossil-C_3</td><td>soil-C_2+
fossil-C_2+
fossil-C_3+
sequestered biogenic-C</td><td>soil-C_2+
fossil-C_2+
fossil-C_3+
sequestered biogenic-C+
biogenic-C_3, CO_2</td></tr>
</table>

[a] LU is land use, while LUC is land use change. CtGt is a boundary for bioenergy at the gate of production facilities, while CtGrv is a complete life cycle boundary. Flows in italic represent biogenic carbon added to complete the inventories. System boundaries, modes of biomass decomposition, and biomass valuation generate different effects on the inventories.

The data in Table 4.2 were employed to illustrate the application of the procedure to quantify global warming impacts exhibited in Table 4.1. The impacts were calculated for the cases where biomass was naturally decomposed or converted into bioenergy. In this regard, total carbon emissions are tentatively determined either as 20 kg CO_2 or 7.27 kg CH_4. This equivalency is based on the fact that the mass of 1 mol CH_4 = 0.3635 mol CO_2. The emissions for biomass products and residues in the last two columns vary, depending on the chosen allocation procedure, which in this case is tentatively determined as 90% for the biomass products and 10% for the biomass residues. The impact assessment method was in accordance with the IPCC guidelines for climate change, where the GWP of CH_4 is equal to 34 CO_2, based on a 100 year time horizon (IPCC, 2013).

Table 4.2. Hypothetical inventories of various carbon flows in bioenergy systems.

Types of carbon flows	Carbon emissions (kg)			
	Total [a] (100%)		Allocation factors: Biomass products (90%)	Allocation factors: Biomass residues (10%)
	CO_2	CH_4	CO_2-eq [b]	
Soil-C_1	20	.	18	2
Soil-C_2	20	.	18	2
Fossil-C_1	20	.	18	2
Fossil-C_2	20	.	18	2
Fossil-C_3	20	.	18	2
Biogenic-C_1	20	.	18	2
Biogenic-C_1, emitted as CH_4	.	7.27	222.3	24.7
Biogenic-C_2	20	.	18	2
Biogenic-C_2, emitted as CH_4	.	7.27	222.3	24.7
Biogenic-C_3	20	.	18	2
Sequestered biogenic-C [c]	-20	.	-18	-2
Biogenic-C, emitted as SOC [c]	0	0	0	0

[a] Based on equal molar, total carbon emissions are tentatively determined either as 20 kg CO_2 or 7.27 kg CH_4. The emissions from biomass products and residues in the last two columns vary, depending on the chosen allocation factors between biomass products and residues, which in this case are tentatively determined as equal to 90% for the biomass products and 10% for the biomass residues.
b Based on the recent IPCC report, global warming potential for 100-year time horizon of 1 kg CH_4 is equal to 34 kg CO_2-eq (IPCC, 2013).
c Considering the directions of the flows in Figure 4.1 which are opposite to the other parameters, the values of *sequestered biogenic-C* and SOC are negative. However, SOC_1 and SOC_2 are in the forms of organic carbon, thus, cannot be expressed in terms of CO_2-eq. To avoid complexity in the analysis, while still achieving the objectives of the paper, the decomposed biomass carbon are all assumed emitted into the atmosphere, thus, SOC_1 and SOC_2 in terms of CO_2-eq are equal to zero.

The carbon neutrality assumption in various inventory situations was examined using a carbon balance based on a life cycle approach. The criterion to include biogenic carbon neutrality assumption could be valid only if the final scores based on excluding biogenic carbon from an inventory were the same as those based on a complete inventory (including biogenic carbon). The latter is further referred to as the ‘true’ values. Deviations of assuming biogenic carbon neutrality from the ‘true’ values are expressed in percentages, which values = ([excluding biogenic-C - including biogenic-C]) / (including biogenic-C).

4.4 Results and discussion

4.4.1 Results

The results regarding global warming performances of various biogenic carbon scenarios are listed in Table 4.3. The percentages in the last column indicate the extent that the results become biased, i.e. the deviation of assuming biogenic-carbon neutrality from the 'true' value based on a complete inventory. These results are further analyzed against the criterion that biogenic carbon neutrality assumption is valid only if no distinction occurs between the final scores based on excluding or including biogenic carbon, thus, the percentages listed in the last column should be zero (see the criterion in Section 3). However, this is not the case; the extent of the bias ranges between -86% to +50%. These values depend on the respective scenarios encompassing specific system boundaries, forms of carbon emissions, and biomass valuation.

Table 4.3. Global warming performances of various carbon flows in bioenergy systems[a].

Sce-nario	Biomass residues decomposed in fields	CO_2-equivalent (kg)				Deviations from the 'true' values (%)	
		Excluding biogenic carbon (carbon neutral)		Including biogenic carbon ('true' values)			
1	At a LUC phase, emitted as CO_2	4		6		-33	
2	At a LUC phase, emitted as CH_4	4		28.7		-86	
3	At a LU phase, emitted as CO_2	4		4		0	
4	At a LU phase, emitted as CH_4	4		26.7		-85	
Biomass products converted into bioenergy		CtGt	CtGrv	CtGt	CtGr	CtGt	CtGrv
5	From a LUC phase	54	54	54	72	0	-25
6	From a LU phase	54	54	36	54	50	0
Biomass residues converted into bioenergy		CtGt	CtGrv	CtGt	CtGr	CtGt	CtGrv
7	From a LUC phase	6	6	6	8	0	-25
8	From a LU phase	6	6	4	6	50	0

[a] This table illustrates results of the operation of the criteria presented in Table 4.1 using data in Table 4.2. LU is land use, while LUC is land use change. CtGt is a boundary for bioenergy at the gate of production facilities, while CtGrv is a complete life cycle boundary. Percentages in the last column = ([excluding biogenic-C - including biogenic-C]) / (including biogenic-C) at the respective system boundaries. They indicate the extent of deviations, which can be positive or negative, from the 'true' values based on a complete inventory (including biogenic-C).

Zero percent means that the biogenic carbon neutrality assumption does not move the global warming impacts away from the values based on complete inventories. These are cases of Scenarios 3, 5-CtGt, 6-CtGrv, 7-CtGt, and 8-CtGrv where the neutrality assumption holds true. In the other scenarios, however, the neutrality assumption clearly introduces substantial biases to the 'true' values. These biases make the final results higher (Scenarios 6-CtGt and 8-CtGt) or lower (Scenarios 1, 2, 4, 5-CtGrv, and 7-CtGrv) from the values based on complete inventories. Higher global warming impacts can be found in Scenarios 6 and 8 that assumed carbon neutrality. These are the effect of excluding the sequestered carbon during plant growth at the land use phase from the inventory.

4.4.2 Discussion

The LCA results listed in Table 4.3 have demonstrated that dissimilar inventory situations (modes of biomass decomposition and biomass valuation) and methodological choices (system boundaries and allocation factors) based on complete inventories can generate various final scores, which are often different from that assuming biogenic carbon neutrality. On the basis of the scope of system boundary, the deviations in Scenarios 5-CtGrv, 6-CtGt, 7-CtGrv, and 8-CtGt are non-zero. These deviations are due to the emissions of biogenic carbon during combustion of bioenergy taking place at the use phase. In addition, the extent of the deviations is different between cradle-to-gate and cradle-to-grave boundaries. In this respect, to acquire the true value, the analysis is ideally carried out on a complete life cycle system boundary (cradle-to-grave) rather than at a cradle-to-gate boundary. It is based on the recognition that a complete inventory will provide a more accurate estimate of carbon balance.

Processes involving anaerobic decomposition (Scenarios 2 and 4) provided substantially greater global warming impacts than aerobic decomposition (Scenarios 1 and 3). These facts demonstrate the effect of decomposition modes under anaerobic conditions which is much more influential on the final results relative to aerobic conditions. This is due to the fact that the GWP of CH_4 from anaerobic decomposition is 34 times, much higher, than that of CO_2 (IPCC, 2013). It is also important to note that not all mineralized carbon in field decomposition would be emitted into the atmosphere; some would be recycled as organic carbon into the soil matrix (see SOC_1 and SOC_2 in Figure 4.1). Such a split of carbon flows between the atmosphere and soil is often neglected in the study of bioenergy LCA, likely due to incomplete knowledge of the inventory of such processes. We speculate that a more refined modeling of the decomposition process may have substantial improvement on the outcomes of bioenergy LCA studies. Further discussion on the impact assessment of SOC can be found in Wiloso et al. (2014).

Biomass valuation plays an important role in determining global warming impacts. For example, the scores of product-based bioenergy (Scenarios 5 and 6) are consistently higher than those from biomass residues (Scenarios 7 and 8) accordingly to the allocation factors, i.e. relative valuation between biomass products and residues. It is also observed that biomass residues have more inventory variations (options to be naturally decomposed in aerobic/anaerobic conditions or converted into bioenergy) than those based on biomass products (converted into bioenergy). Similarly, global warming scores of biomass residues valued as goods (having positive economic values) would generally be higher than those valued as wastes (having negative economic values). This is an important observation since biomass residues can be valued either as goods or as wastes, depending on regulations or market prices.

As indicated earlier, the assumption on biogenic carbon neutrality has been questioned primarily on the basis of changes in soil carbon stock due to LUC (Searchinger et al., 2008) and carbon storage capacities of long-rotation trees (Cherubini et al., 2011) or wood products (Levasseur et al., 2012, 2013). In this regard, the current study provides additional arguments that, indeed, the assumption on biogenic carbon neutrality introduces a bias to the 'true' values. Also, this analysis establishes the advantages of a life cycle approach to examine carbon neutrality assumption whereby the variation in final scores due to different system boundary, forms of carbon emissions, and biomass valuation cannot be easily revealed using a carbon stock method, an approach typically used by IPCC (Levasseur et al., 2013).

The results presented here require proper interpretation since they are based on certain hypothetical inventory data. Further analysis exploiting actual inventory data, for example, those available in literature, may be necessary to further verify if the conclusion for the non-neutrality assumption of biogenic carbon is also valid for other inventory situations. In this regard, the absolute values of the variations (-86% to +50%) may not be of particular importance since they would fluctuate accordingly, depending on the inputted inventory data. However, the predominant message of the study has convincingly reported substantial deviations in the global warming results if biogenic carbon is excluded from the inventory.

The literature study also reveals that divergence in ways to develop carbon inventories is in general more extensively found in scientific literatures of bioenergy LCA than in policy guidelines. This is quite a surprising observation that [1] many scientific articles tend to give no consideration to biogenic carbon because of the neutrality assumption and [2] attitude towards the adoption of this assumption varies depending on the forms of bioenergy. The latter can be distinguished clearly between LCA studies on solid bioenergy and second-generation (liquid) biofuel. We speculate that in the future such divergence in the area of bioenergy might adjust towards a more harmonized LCA approach. This is in accordance with the tendency in policy guidelines that additional scientific publications would adopt more the concept of utilizing a complete inventory rather than assuming carbon neutrality.

4.5 Conclusions

This study demonstrates that the global warming impacts of scenarios based on the LCA principles, treating all relevant input-outputs as genuine flows (including biogenic carbon), provides various results which are in many cases different from those assuming biogenic carbon neutrality (excluding biogenic carbon). In addition to the existing arguments of carbon stock change (Searchinger et al., 2008) and carbon storage capacities of long-rotation trees (Cherubini et al., 2011) or wood products (Levasseur et al., 2012, 2013), the current study supports the assertion that the assumption on biogenic carbon neutrality introduces biases to the 'true' values based on a complete inventory. The extent of such a bias, which can make the values of global warming impacts substantially higher or lower, depends on specific situations. Three factors are identified to substantially propagate biases in the evaluation of global warming performances of a bioenergy system. They are differences in framing system boundaries (cradle to grave vs. cradle to gate), forms of carbon emissions (CO_2 vs. CH_4), and valuation of biogenic carbon (biomass products vs. biomass residues). The results of this study are expected to contribute to the harmonization of future bioenergy LCA by directing further research to adopt more the concept of utilizing a complete inventory rather than the neutrality assumption.

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4.7 References

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