Biogenic Carbon and Temporary Storage Addressed with Dynamic Life Cycle Assessment

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Key words:

carbon footprint
carbon storage
climate change
global warming
industrial ecology
time

Summary

A growing tendency in policy making and carbon footprint estimation gives value to temporary carbon storage in biomass products or to delayed greenhouse gas (GHG) emissions. Some life cycle-based methods, such as the British publicly available specification (PAS) 2050 or the recently published European Commission's *International Reference Life Cycle Data System (ILCD) Handbook*, address this issue. This article shows the importance of consistent consideration of biogenic carbon and timing of GHG emissions in life cycle assessment (LCA) and carbon footprint analysis. We use a fictitious case study assessing the life cycle of a wooden chair for four end-of-life scenarios to compare different approaches: traditional LCA with and without consideration of biogenic carbon, the PAS 2050 and *ILCD Handbook* methods, and a dynamic LCA approach. Reliable results require accounting for the timing of every GHG emission, including biogenic carbon flows, as soon as a benefit is given for temporarily storing carbon or delaying GHG emissions. The conclusions of a comparative LCA can change depending on the time horizon chosen for the analysis. The dynamic LCA approach allows for a consistent assessment of the impact, through time, of all GHG emissions (positive) and sequestration (negative). The dynamic LCA is also a valuable approach for decision makers who have to understand the sensitivity of the conclusions to the chosen time horizon.

Introduction

Over the last few years there has been growing concern about the lack of consideration for temporal aspects of greenhouse gas (GHG) emissions in life cycle assessment (LCA) and carbon footprint analysis. Two different factors explain this concern: (1) an increasing will in policies and carbon footprint methods to give value to temporary carbon storage, and (2) the inconsistency in time frames when assessing the impact of GHG emissions, even when adopting global warming potentials (GWPs) with a fixed time horizon. Another topical issue regarding the assessment of GHG emissions is the consideration of biogenic carbon, for which there is no consensus among different methods. Using a fictitious case study comparing different approaches, the objective of this article is to show that the results of a life cycle GHG assessment are sensitive to the assumptions regarding the timing of emissions and the consideration of biogenic carbon, and that dynamic LCA is the preferred approach to address these issues consistently.

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DOI: 10.1111/j.1530-9290.2012.00503.x

Volume 17, Number 1

Temporal Issues in Global Warming Impact Assessment

GWPs, developed by the Intergovernmental Panel on Climate Change (IPCC), express the cumulative radiative forcing over a given time horizon of a unit mass pulse emission of GHG, divided by the same value for carbon dioxide (CO_2) (Forster et al. 2007). Using GWPs for a given time horizon (e.g., 20, 100, or 500 years) to assess the impact of GHG emissions implies that one considers the radiative forcing occurring over a time period between the moment when the emission occurs and the year corresponding to the chosen time horizon, without any discounting for time. For long-lived products or projects, for which GHG emissions are occurring at different moments over several years, the time frame covered by the LCA results is not consistent with the chosen time horizon for GWPs. Indeed, if a 100-year time horizon is chosen, the first life cycle emission is actually assessed over the first 100 years, but an emission occurring at the end of life of a 50-year lifetime product is assessed from year 50 to year 150. Therefore, when comparing LCAs for different long-lived products or projects, the temporal boundaries of the global warming impact category are not necessarily the same, which can bias the conclusions. O'Hare and colleagues (2009) and Levasseur and colleagues (2010) have explained the problem of the inconsistency between the time frame chosen for the analysis and the time period covered by the LCA results.

Researchers have proposed some approaches to improve the assessment of delayed emissions. Kendall and colleagues (2009) and O'Hare and colleagues (2009) addressed the particular case of land use change emissions in biofuels studies, which occur mostly during the first year of biofuel feedstock production, and are then paid back by the GHG emissions reduction caused by replacing fossil fuels with biofuels during the following years. They both proposed methods to consistently assess the impact of fossil fuels replacement with biofuels over a given time frame. Other approaches, such as the publicly available specification (PAS) 2050 (BSI 2008) and the *International Reference Life Cycle Data System (ILCD) Handbook* (European Commission 2010) propose methods to address delayed GHG emissions in LCA. Both multiply each life cycle GHG emission, previously converted into kilograms CO_2 equivalent (kg CO_2-eq) using GWPs, by a weighting factor to account for the average time the gas is present in the atmosphere over a 100-year assessment period.[1] This means that the later a GHG emission occurs, the shorter its residence time in the atmosphere over the 100-year time frame, and the lesser its impact on global warming, until the impact goes to zero for an emission occurring after 100 years.

The methods proposed by PAS 2050 and the *ILCD Handbook* also allow accounting for temporary carbon storage in long-lived products. Whether or not to give value to the act of keeping carbon out of the atmosphere for a given period of time is a hotly debated issue. Temporary carbon storage has been strongly criticized, as it could worsen certain impacts on climate change. The cumulative radiative forcing calculated over a given time frame decreases when carbon is stored, reducing the climate impacts caused by cumulative heating, such as the melting of ice caps. However, some studies with climate models have shown that taking carbon out of the atmosphere and releasing it back several years later can lead to a higher atmospheric concentration of CO_2, and thus a higher temperature at some point in time, than if the carbon had not been stored (Kirschbaum 2006; Korhonen et al. 2002). This higher temperature can increase the frequency of extreme meteorological events or the incidence of some heat-related diseases. One argument in favor of temporary carbon storage is that it buys time for mitigation while technologies and knowledge are evolving (Dornburg and Marland 2008; Noble and Scholes 2001).

Current LCA methodologies are not equipped to give any value to temporary carbon storage, as the amount of sequestered carbon would be subtracted from the emission occurring at the end of the storage period to give a net zero emission (Levasseur et al. 2012b). Besides the two previously cited approaches, other carbon footprint standards and GHG accounting methods that provide guidance on how to assess for temporary carbon storage in long-lived products have recently been published (AFNOR 2009; WRI/WBCSD 2011) or are yet to come (ISO 2011). The European Union's Joint Research Centre also organized an expert workshop to give guidance on how to assess temporary carbon storage in LCA and carbon footprint analysis (Brandão and Levasseur 2011).

The Issue of Biogenic Carbon

The IPCC guidelines for national GHG inventories consider that carbon contained in biomass is released when harvested, following a stock change approach for which net emissions are estimated by calculating the net changes in carbon stocks of a biomass carbon pool over time (IPCC 2006). This approach contrasts with the flow approach, for which emissions are estimated by directly considering GHG flows to and from the atmosphere (IPCC 2006). Using the IPCC guidelines, to avoid double counting, if biogenic carbon is released later in the life cycle, such as during the combustion of bioenergy, the related CO_2 emissions are not accounted for. This widely used assumption about biomass carbon neutrality is increasingly criticized (Searchinger et al. 2009). Recent publications brought to light the concept of bioenergy carbon debt (EEA 2011; MCCS 2010; McKechnie et al. 2011). The combustion of biomass causes more GHG emissions per unit of energy compared to the use of fossil fuels, creating a carbon debt. Then the debt is paid down as the biomass grows up and sequesters carbon from the atmosphere. However, by the time the biomass grows up, the additional amount of carbon released by the replacement of fossil fuels with bioenergy has an impact on climate, especially for wood, because forests often take decades to mature.

Currently in LCA, impact assessment often excludes biogenic CO_2 emissions, as it assumes that the same amount of CO_2 was previously sequestered by biomass, giving a net zero emission (Guinée et al. 2002; Hischier et al. 2010). A few guidebooks discuss the importance of accounting for biogenic CO_2 in some particular cases, such as forestry projects for carbon sequestration in biomass, agricultural systems, or when biogenic

CO_2 emissions are coming from deforestation of primary forest and land transformation (Guinée et al. 2002; Hischier et al. 2010).

Guinée and colleagues (2009) have shown that for agricultural products and systems that contain multifunctional processes, it may be relevant to consider positive and negative biogenic CO_2 emissions. Indeed, carbon uptake by biomass usually does not occur in the same unit process as its associated biogenic carbon emission. The application of different methods for dealing with multifunctionality on these processes, such as allocation, can therefore give different results depending on whether or not biogenic carbon is considered. Christensen and colleagues (2009) have shown that the lack of consideration for biogenic CO_2 in LCA modeling of waste management can also lead to biased results because it eclipses potentially permanent carbon sequestration (e.g., in landfills) that would decrease the impact on global warming.

The way biogenic carbon is treated in LCA and carbon footprint methods that account for temporary carbon storage and delayed GHG emissions varies. According to PAS 2050 (BSI 2008), we should not consider biogenic CO_2 uptakes and emissions. Biogenic methane (CH_4) and nonbiogenic GHG emissions should be multiplied by their respective GWP_{100} value and by a factor that expresses the weighted average time the emission is present in the atmosphere during the 100-year assessment period. Finally, we should calculate the benefits for storing biogenic carbon by multiplying the amount of carbon stored in a product by a factor that reflects the weighted average time of storage during the 100-year assessment period. The *ILCD Handbook* (European Commission 2010) recommends considering biogenic carbon uptakes (negative value) and emissions (positive value). According to this method, we should multiply every GHG emission by its respective GWP_{100} value and by the fraction of time the emission is present in the atmosphere relative to the 100-year assessment. This means that an emission occurring at time zero is multiplied by 1, an emission occurring after 50 years is multiplied by 0.5, and one occurring after 100 years is multiplied by 0.

Cherubini and colleagues (2011a, 2011b) recently proposed an alternative approach to assess the climate impact of biogenic CO_2 emissions coming from biomass combustion in LCA. They developed GWP_{bio} indices for different biomass rotation periods and analytical time horizons to use as characterization factors for global warming to account for the climate impact of biogenic CO_2 before it is recaptured by biomass regrowth.

The Dynamic Life Cycle Assessment Approach

A dynamic LCA approach to account for the timing of emissions in LCA (Levasseur et al. 2010) uses a dynamic inventory, which details each emission through time (i.e., the amount of pollutant released at every given time-step), and dynamic characterization factors to determine the impact of emissions for every time-step. Dynamic characterization factors for the global warming impact category integrate the radiative forcing expression for each GHG over a time period included between the emission time and a selected time horizon. The results of this approach thus express the time-dependent radiative forcing caused by the GHG life cycle emissions.

We first applied the dynamic LCA approach to a case study assessing GHG emissions reduction caused by the replacement of fossil fuels with biofuels while considering land-use change emissions. This showed how the dynamic LCA can address the issue of temporal inconsistency described previously (Levasseur et al. 2010). We then applied the method to a carbon sequestration and storage project through forestry to show how it can provide the temporal resolution necessary for the assessment of temporary carbon storage (Levasseur et al. 2012b). Dynamic LCA assesses every GHG consistently using its specific radiative forcing time-dependent curve. This allows analysis of the sensitivity of the results to the choice of a time horizon, as it is not fixed at the beginning of the study.

The objective of this article is to demonstrate the importance of considering biogenic carbon and the timing of GHG emissions with consistency. The comparison of existing approaches shows how the inclusion of biogenic carbon, as well as different time-related modeling choices, lead to a change in LCA results and conclusions, and how dynamic LCA can help set transparent temporal boundaries and consistently address the timing of emissions and sequestration related to these boundaries. This is done using an illustrative case study performed on a fictitious wooden chair for four end-of-life scenarios with five different methods: (1) a traditional LCA approach that does not account for biogenic carbon, (2) a traditional LCA approach modified to account for biogenic carbon uptake and emissions, (3) the application of the PAS 2050 carbon footprint specification, (4) the application of the *ILCD Handbook* method, and (5) the dynamic LCA approach.

Methodology

We developed a fictitious case study comparing the life cycle GHG emissions of a wooden chair using five different approaches for four end-of-life scenarios: incineration, landfilling, refurbishment, and incineration with energy recovery.

Comparison of Four End-of-Life Scenarios for a Wooden Chair

The chair has a 50-year lifetime and is made of 5 kg of black spruce. For simplification purposes, the calculation considers only two GHGs (i.e., CO_2 and CH_4). The functional unit of this case study is "the use of a wooden chair for 100 years." Therefore, for each scenario, the consecutive life cycles of two chairs are modeled (see table 1). It is assumed that the production of the first and second chairs is equivalent.

On year 1, the first chair is built and trees are planted to renew the resource. These trees are assumed to grow over the next 70 years, sequestering carbon from the atmosphere. Some fossil emissions are also associated with the production of raw

Table 1 Description of the wooden chair case study for four end-of-life scenarios

	Incineration	*Landfill*	*Refurbishment*	*Energy recovery*
Year 1	Chair 1 is built from raw materials Trees are planted and will grow for the next 70 years	Chair 1 is built from raw materials Trees are planted and will grow for the next 70 years	Chair 1 is built from raw materials Trees are planted and will grow for the next 70 years	Chair 1 is built from raw materials Trees are planted and will grow for the next 70 years
Year 50	Chair 1 is burned without energy recovery	Chair 1 is landfilled (emissions of CO_2 and CH_4 over 500 years without gas recovery)	Chair 1 is refurbished, resulting in chair 2	Chair 1 is burned with heat recovery avoiding the use of fuel oil
	Chair 2 is built from raw materials Trees are planted and will grow for the next 70 years	Chair 2 is built from raw materials Trees are planted and will grow for the next 70 years		Chair 2 is built from raw materials Trees are planted and will grow for the next 70 years
Year 100	Chair 2 is burned without energy recovery	Chair 2 is landfilled (emissions of CO_2 and CH_4 over 500 years without gas recovery)	Chair 2 is landfilled (emissions of CO_2 and CH_4 over 500 years without gas recovery)	Chair 2 is burned with heat recovery avoiding the use of fuel oil

Notes: CO_2 = carbon dioxide; CH_4 = methane.

materials, and residues coming from forest exploitation (branches, leaves, etc.) are burned without energy recovery, releasing biogenic CO_2. After its lifetime (50 years), the chair is burned, releasing its carbon content to the atmosphere (incineration and energy recovery scenarios); landfilled, releasing a small part of its carbon content to the atmosphere over a period of 500 years (landfill scenario); or refurbished, prolonging the carbon storage (refurbishment scenario). That same year, a second chair is either built from raw materials and trees are planted again (incineration, energy recovery, and landfill scenarios), or results from the refurbishment of chair 1 (refurbishment scenario). On year 100, the second chair is burned (incineration and energy recovery scenario), or landfilled (landfill and refurbishment scenarios). For the energy recovery scenario, heat coming from burning the chairs at their end of life is recovered and the emissions caused by an equivalent amount of heat produced with fuel oil are avoided.

We calculate a dynamic inventory for each scenario by compiling yearly emissions using the data presented in table 2. All the CO_2 and CH_4 emissions are included, whether they are from fossil or biogenic sources. Sequestration of CO_2 in trees is treated as a negative emission, because it reduces the amount of atmospheric CO_2, leading to a negative radiative forcing following a symmetric profile compared to a positive emission (Korhonen et al. 2002; Levasseur et al. 2012b). Cherubini and colleagues (2011a) present an extensive analysis of the role of biogenic CO_2 emissions and sequestrations in the global carbon cycle. Emissions coming from other life cycle processes are considered equivalent for every scenario and are not included in the inventory (manufacturing of the chair or refurbishment, transportation, etc.).

The forest carbon balance comes from a study conducted by Gaboury and colleagues (2009) on the afforestation of open woodlands in Quebec, Canada's boreal forest. They calculated carbon flows between the forest and the atmosphere by estimating the yearly carbon stock changes of the afforestation project compared to the natural regeneration of open woodlands. The carbon balance is negative for the first 20 years, which means that the forest is a net emitter of CO_2, as the loss from decomposition of organic matter is greater than the gain from the growth of trees. The preparation of the soil prior to planting is responsible for this decrease in carbon content. We assume that the residues from forest exploitation (41% of the total amount of carbon sequestered) are burned without energy recovery, and that the carbon sequestered in the soil (12% of the total) stays on site. If trees are cut again, the increase in decomposition of this organic matter will be taken into account in the following reforestation carbon balance. It would be possible with this approach to build a dynamic inventory using different assumptions regarding forest management practices, such as keeping the residues on the ground and letting them decompose, or using them as bioenergy, to model any type of product system.

Calculation of the Global Warming Impact Following Five Different Approaches

Five different approaches provided results for the assessment of the global warming impact of the wooden chair.

Dynamic Life Cycle Assessment

The dynamic LCA approach, developed by Levasseur and colleagues (2010), first calculates the instantaneous and

Table 2 Data sources used for the calculation of the dynamic inventories

Data category	*Type of data*	*Comment*	*Reference*
Raw materials	Fossil emissions from forestry and sawmill activities		Sawn timber, softwood, planed, kiln dried, RER, at plant, Ecoinvent database v2.2
Biogenic carbon contained in the chair	Carbon content of black spruce wood and number of trees needed to build a chair	Released completely when the chair is burned or partially following landfill	Gaboury et al. (2009)
Biogenic emissions from burning of wood residues	Distribution of the carbon in the different parts of the tree	Noncommercial part of the stem, branches, and roots are burned when trees are cut	Gaboury et al. (2009)
Growth of trees	Biogenic carbon sequestration curve	The carbon balance has been determined for black spruce in boreal forests over 70 years	Gaboury et al. (2009)
Heat produced from wood	Fossil emissions caused by the process of heat production from wood in a furnace		Heat, softwood chips from industry, at furnace, 50 kW, Ecoinvent database v2.2
Heat produced from fuel oil	Emissions caused by the process of heat production from fuel oil	Avoided emissions for the energy recovery scenario	Heat, light fuel oil, at boiler 100 kW, nonmodulating, Ecoinvent database v2.2
Landfill	Total biogenic carbon released from the landfilled wood	3.2% of the carbon contained in landfilled wood is degraded	Micales and Skog (1997)
Landfill	Dynamic of landfill gas production	Landfill gas production (CO_2 and CH_4) per year over 500 years	Sich and Barlaz (2000)

Notes: CO_2 = carbon dioxide; CH_4 = methane; one kilowatt (kW) ≈ 56.91 British Thermal Units (BTU)/minute ≈ 1.341 horsepower (HP).

cumulative impacts on global warming $GWI_{\text{inst}}(t)$ and $GWI_{\text{cum}}(t)$, respectively, following equations (1) through (3):

$$DCF(t) = \int_{t-1}^{t} a \times C(t)dt \tag{1}$$

$$\begin{aligned} GWI_{inst}(t) = & \sum_{i=0}^{t} \left[g_{CO_2}(i) \times DCF_{CO_2}(t-i) \right] \\ & + \sum_{i=0}^{t} \left[g_{CH_4}(i) \times DCF_{CH_4}(t-i) \right] \end{aligned} \tag{2}$$

$$GWI_{cum}(t) = \sum_{i=0}^{t} GWI_{inst}(i), \tag{3}$$

where $DCF(t)$ is the dynamic characterization factor used to assess a GHG emission that occurred t years before (in watts per year per square meter [W/yr/m^2]),[2] a is the instantaneous radiative forcing per unit mass increase in the atmosphere for the given GHG (in W/m^2/kg), $C(t)$ is the atmospheric load of the given GHG t years after the emission (in kg), and $g(i)$ is the inventory result (sum of the positive and negative emissions) of the given GHG for year i (in kg).

The dynamic characterization factor, $DCF(t)$, expresses the radiative forcing occurring t years after a pulse emission (equation 1). The instantaneous global warming impact $GWI_{\text{inst}}(t)$ occurring at a given time t is thus obtained by summing the radiative forcing occurring at time t caused by each previous life cycle GHG emission, which is determined by multiplying each of these emissions by the dynamic characterization factor calculated for the period elapsed between the emission and time t (equation 2). For instance, the radiative forcing occurring at time t caused by an emission released ten years before is given by multiplying the amount of gas released by $DCF(10)$. Finally, the cumulative global warming impact, $GWI_{\text{cum}}(t)$, is the sum of the GWI_{inst} calculated for all the previous years (equation 3). It expresses the total amount of increased radiative forcing caused by the studied life cycle GHG emissions over a given time period.

In order to compare the cumulative global warming impact, GWI_{cum}, with the results coming from a traditional LCA approach, a time horizon, TH, is chosen and the cumulative impact on global warming for this time horizon $GWI_{cum}(TH)$ is divided by the cumulative radiative forcing of a 1 kg CO_2 pulse emission occurring at time zero to get the global warming impact, LCA_{dyn} (in kg CO_2-eq) (equation 4):

$$LCA_{dyn} = \frac{GWI_{cum}(TH)}{\int_0^{TH} a_{CO_2} \times C(t)_{CO_2} dt}. \quad (4)$$

Traditional Life Cycle Assessment without and with Consideration of Biogenic Carbon

We recalculated the results in what was called a "traditional LCA without biogenic CO_2" model ($LCA_{without}$), where the sum of all the fossil CO_2 emissions, and the sum of all the fossil and biogenic CH_4 emissions are multiplied by their respective GWP for the two time horizons most often used in life cycle impact assessment: 100 and 500 years (equation 5). In order to look at the effect of not considering biogenic CO_2 emissions and sequestration, we performed a "traditional LCA with biogenic CO_2" (LCA_{with}) by adding them to the inventory (equation 6).

$$\begin{aligned} LCA_{without} = & \sum_t g_{CO_2\,fossil}(t) \times GWP_{TH}^{CO_2} \\ & + \sum_t g_{CH_4\,fossil+biogenic}(t) \times GWP_{TH}^{CH_4} \end{aligned} \quad (5)$$

$$\begin{aligned} LCA_{with} = & \sum_t g_{CO_2}(t) \times GWP_{TH}^{CO_2} \\ & + \sum_t g_{CH_4}(t) \times GWP_{TH}^{CH_4} \end{aligned} \quad (6)$$

Publicly Available Specification 2050 and International Reference Life Cycle Data System Handbook

Finally, we assessed the global warming impact of the wooden chair for the four end-of-life scenarios using the PAS 2050 specification and the *ILCD Handbook* method, which account for carbon storage and delayed emissions (BSI 2008; European Commission 2010). We assessed each of the two chairs needed for the functional unit individually, and then summed the results.

Following the PAS 2050 specification's guidelines, every fossil and non-CO_2 biogenic emission is multiplied by its respective GWP_{100}. A credit (i.e., a negative value in kg CO_2-eq) is then added to account for the impact of storing biogenic carbon during the chairs' lifetimes (equation 7).

$$\begin{aligned} LCA_{PAS2050} = & \sum_t g_{CO_2\,fossil}(t) \times GWP_{100}^{CO_2} \\ & + \sum_t g_{CH_4\,fossil+biogenic}(t) \\ & \times GWP_{100}^{CH_4} - Credit \end{aligned} \quad (7)$$

PAS 2050 determines the credit using the weighted average time of storage over the 100-year assessment period (equation 8). Carbon stored for more than 100 years is considered permanently stored:

$$Credit = [kgCO_2stored] \times \frac{\sum_{i=1}^{100} x_i}{100}, \quad (8)$$

where i is each year the storage occurs, and x is the proportion of total storage remaining in any year i.

According to the *ILCD Handbook* method, we multiplied every biogenic and fossil GHG emission by its respective GWP_{100}, as well as biogenic CO_2 uptake, which is considered a negative emission occurring when the trees are cut. Then we added a credit to account for the weighted average time of storage over the 100-year assessment period (equation 9).

$$\begin{aligned} LCA_{ILCD} = & \sum_t g_{CO_2}(t) \times GWP_{100}^{CO_2} \\ & + \sum_t g_{CH_4}(t) \times GWP_{100}^{CH_4} - Credit \end{aligned} \quad (9)$$

The credit is obtained by multiplying every delayed emission (i.e., every emission occurring later than year 1) by its respective GWP_{100}, the number of years of delay (or storage) t, and 0.01 kg CO_2-eq/kg/yr (equation 10). The equivalency factor (0.01 kg CO_2-eq/kg/yr) is based on the assumption that storing 1 kg CO_2 during 100 years compensates a 1 kg CO_2-eq emission, which is then equally divided over the storage period. As for PAS 2050, carbon released after 100 years is considered permanently stored.

$$Credit = \sum_{t=2}^{100} g_i(t) \times GWP_{100}^{i} \times t \times 0.01 \quad (10)$$

Sensitivity Analysis Performed on the Timing of the Sequestration

A sensitivity analysis shows the impact of considering the sequestration of carbon in growing trees before or after the manufacturing of the chair. In the original case study, the carbon sequestration occurs after the manufacturing of the chair, assuming that trees are planted after the exploitation to ensure the sustainability of the resource. The aim of this sensitivity analysis is to show that the timing of the emissions (negative or positive) can significantly change LCA results.

We calculated a dynamic inventory for the life cycle of one wooden chair burned at its end of life using the data found in table 2. For the "before" scenario, the sequestration occurs from year −70 until year 0, while trees are growing. At year 1, trees are cut, the chair is built, and it is then burned without energy recovery 50 years later. For the "after" scenario, the chair is built and burned at the same points in time as the "before" scenario (0 and 50 years, respectively), but the carbon sequestration occurs from year 1 to year 71, as trees are planted right after the manufacture of the chair. The instantaneous and cumulative impacts on global warming are then calculated for both scenarios using equations (2) and (3).

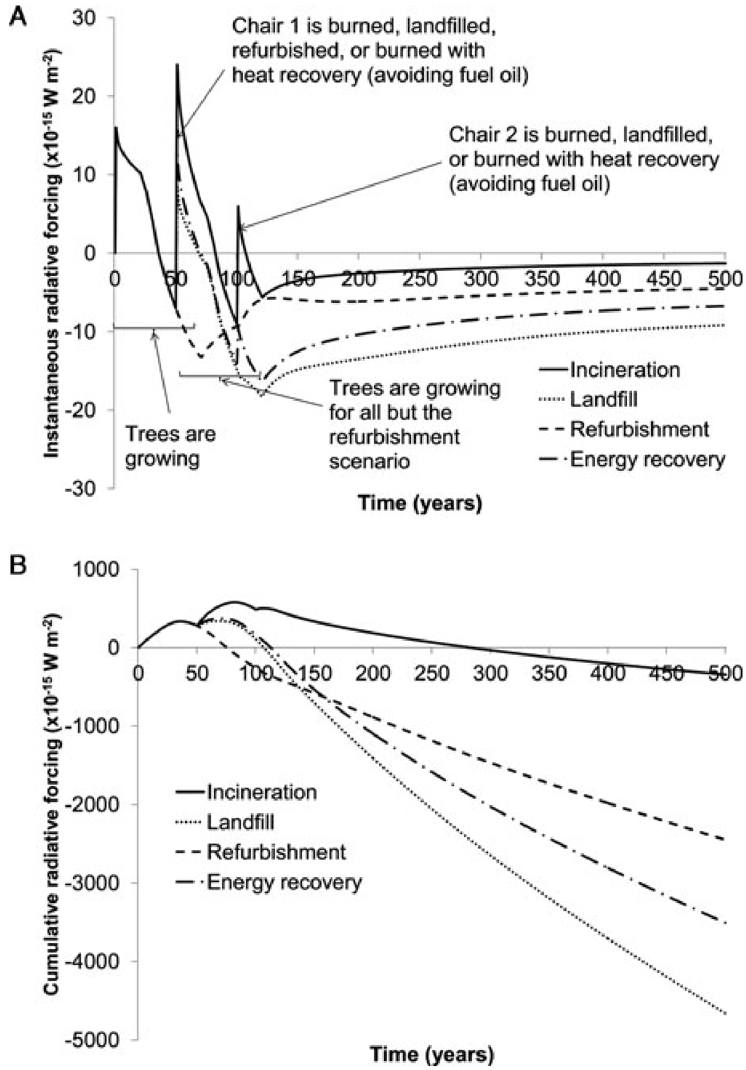

Figure 1 Instantaneous (a) and cumulative (b) global warming impact of two wooden chairs for four end-of-life scenarios calculated using the dynamic life cycle assessment approach. W = watts.

Results and Discussion

Comparison of Four End-of-Life Scenarios for a Wooden Chair

Figures 1a and 1b present, respectively, the instantaneous and cumulative impacts on radiative forcing of two wooden chairs, calculated using the dynamic LCA approach.

For the first 50 years, which corresponds to the lifetime of the first chair, the impact is the same for every scenario. On year 1, there is an increase in instantaneous radiative forcing, caused by GHG emissions related to the manufacture of the first chair (forestry and sawmill activities, incineration of wood residues). During the following 70 years, the sequestration of carbon in growing trees contributes to the decrease in radiative forcing. At year 50, the incineration scenario shows another increase in radiative forcing caused by the GHG emissions coming from the manufacture of the second chair, and from the burning of the first chair (in the cases of incineration and energy recovery). The increase in radiative forcing for the energy recovery scenario is lower because of the avoided emissions associated with heat recovery from burning chair 1. For the landfill scenario, the increase is also lower than for the incineration scenario because the first chair is not burned, but landfilled, releasing only 3.2% of the carbon content as CO_2 and CH_4 over the following 500 years. Finally, the instantaneous impact for the refurbishment scenario continues to decrease as none of these emissions occur: the first chair is simply refurbished. (It is assumed that there are no emissions for refurbishment activities, as they are set equal to the emissions caused by the manufacturing of the second chair in other scenarios). For the incineration, energy recovery, and the landfill scenarios, new trees are planted at year 50 to replace those that have been cut to build the second chair. For the following 20 years (until year 70), carbon sequestration in the first and the second plantings are both contributing to the decrease in radiative forcing. At year 100, only the incineration scenario shows a significant increase in instantaneous radiative forcing caused by the burning of the second chair. For the energy recovery scenario, the increase is much lower because of the avoided emissions associated with heat recovery. Both the landfill and the refurbishment scenarios have their second chair landfilled, so that the end-of-life emissions are low and extended over 500 years. An inflexion point is observed at 120 years for three scenarios (incineration, energy recovery, and landfill) because the sequestration of carbon in trees, which implies negative emissions, is finished. Then the curves slowly tend to their equilibrium value, which is given by the radiative forcing caused by the residual CO_2 in the atmosphere, because the concentration following a net pulse emission never goes back to the pre-emission level.

The results for the cumulative radiative forcing show that the incineration scenario has the greatest impact on global warming for any time horizon. This is because there is no permanent carbon sequestration associated with the chairs' end of life as they are burned, compared with the landfill and refurbishment scenarios, where the chairs are landfilled and release only 3.2% of their biogenic carbon to the atmosphere, or to the energy recovery scenario, for which fossil emissions are avoided. The cumulative radiative forcing for the incineration scenario becomes negative around year 280 instead of approaching zero. This can be explained by the carbon balance for black spruce in boreal forests used to model carbon sequestration in trees, which shows that a part of the sequestered carbon goes into the soil and stays there, which is considered a permanent sequestration under the assumption the land stays forested.

The conclusion of the comparison between the energy recovery, the landfill, and the refurbishment scenarios for cumulative radiative forcing depends on the chosen time horizon. The cumulative impacts for the energy recovery and the landfill scenarios are quite close for any time horizon less than 150 years, and the different assumptions used to calculate their inventories (e.g., furnace efficiency, type of fossil fuel avoided, landfill conditions, etc.) can decide which one is the best.

Before year 135, the energy recovery and landfill scenarios have a greater impact on cumulative radiative forcing than the refurbishment scenario, but after that time period it is the opposite. The energy recovery and landfill scenarios cause higher GHG emissions at year 50 because of the forest exploitation, sawmill processes, and residue burning necessary to build the second chair, which are not needed in the refurbishment scenario, where the second chair is built from the first one. This leads to a higher cumulative radiative forcing over the short term. However, the use of virgin wood for the second chair implies that a new amount of carbon is captured in trees, compared to the refurbishment scenario, and then permanently sequestered at 96.8% when the chair is landfilled or used to avoid fossil emissions, in the case of energy recovery. Therefore, over the long term in this specific fictitious case study, it is better to landfill or use as fuel the wood products than it is to refurbish them. When landfilled or used as fuel, carbon is taken out of the atmosphere and kept in a permanent sink (landfill) or used to generate permanent fossil fuel emissions reductions (energy recovery).

For the landfill scenario, this conclusion is derived only from a cumulative radiative forcing point of view and is probably not applicable to any other impact categories. Zeng (2008) published a study exploring the idea of harvesting trees and burying them or storing them in above-ground shelters as a climate mitigation initiative, including a discussion about the advantages and potential issues. Another limit of the analysis presented in this article is a reliance on simplified assumptions regarding forest management practices. The forest carbon balance used to calculate carbon flows between the forest and the atmosphere stops 70 years after planting and assumes that no emissions or sequestration occur after. It also represents afforestation of open woodlands where natural regeneration is poor. This increases the benefits given to forest exploitation, as afforestation sequesters a large amount of carbon compared to natural regeneration. The benefits of forest exploitation would also have decreased if we had set the baseline as a natural healthy forest or had considered the additional amount of carbon sequestered when the forest is kept untouched. This is the case at year 50 of the refurbishment scenario, when chair 2 is built from chair 1 instead of from virgin wood. The aim of the case study presented in figure 1 is not to draw conclusions about different end-of-life scenarios for wood products, but to show how dynamic LCA can simultaneously and consistently address both biogenic CO_2 and timing issues of GHG flows.

Table 3 shows the results from dynamic LCA, traditional LCA with and without biogenic CO_2, PAS 2050, and the *ILCD Handbook* method, calculated as per the respective descriptions provided in the methodological section. The methodologies proposed by the PAS 2050 specification and the *ILCD Handbook* could be used with a 500-year time horizon. However, because these methods are usually applied as they stand (using a 100-year time horizon), table 3 does not contain any value for 500 years.

The traditional LCA results (LCA_{without}) do not consider any biogenic CO_2 released or sequestered, and do not consider the temporal profile of the emissions at all. The energy recovery scenario is significantly better than the others because the fossil GHG emissions are avoided when the chairs are burned at their end of life. Because biogenic CO_2 emissions are not considered, the only difference between incineration and landfilling is the amount of biogenic CH_4 released after the chair is landfilled. And because GWP for CH_4 is higher for a 100-year time horizon than for a 500-year time horizon, the choice of preferred scenario differs with the time horizon chosen.

The traditional LCA with biogenic CO_2 (LCA_{with}) considers the biogenic CO_2 emissions and sequestrations along the life cycle inventory. For both time horizons, the landfill scenario becomes more favorable because an important amount of carbon is permanently sequestered in the landfill. The comparison between the LCA_{with} and LCA_{without} results shows that the lack of consideration for biogenic CO_2 can lead to biased conclusions.

Table 3 Comparison of the results obtained with five different approaches for 100- and 500- year time horizons (in kg CO_2-eq)

	100 years				500 years			
Method	*Incineration*	*Landfill*	*Refurbishment*	*Energy recovery*	*Incineration*	*Landfill*	*Refurbishment*	*Energy recovery*
LCA_{dyn}	5.6	1.2	**−3.0**	1.8	−1.2	**−16.3**	−8.6	−12.3
$LCA_{without}$	2.3	5.5	2.7	**−10.3**	2.2	2.9	1.5	**−10.2**
LCA_{with}	−2.6	**−17.5**	−8.6	−15.1	−2.7	**−20.0**	−10.0	−15.1
$LCA_{PAS2050}$	−6.9	**−13.5**	−11.3	−4.1	N/A	N/A	N/A	N/A
LCA_{ILCD}	−11.8	**−20.2**	−14.7	−17.9	N/A	N/A	N/A	N/A

Notes: LCA categories refer to dynamic LCA, traditional LCA without and with biogenic CO_2, PAS 2050, and the *ILCD Handbook* method, respectively. kg CO_2-eq = kilograms carbon dioxide equivalent.

The PAS 2050 specification ($LCA_{PAS2050}$) does not assess biogenic CO_2 emissions, but instead assumes that an equivalent amount of CO_2 has been sequestered in the recent past. A credit, represented by a negative emission, is given for any delayed emission (fossil or biogenic). This credit is proportional to the fraction of the 100-year time period following a product's formation during which its emissions will be in the atmosphere. The results show that, according to the PAS 2050, the landfill scenario is better than the others because of permanent carbon sequestration. The landfill scenario is also preferred according to the *ILCD Handbook* method (LCA_{ILCD}). The major difference between these two is that the ILCD method considers biogenic CO_2 emissions in the calculations, while the PAS 2050 does not.

The three major differences between the PAS 2050 and *ILCD Handbook* on the one hand and dynamic LCA on the other hand are (1) the choice of a time horizon, which is fixed at 100 years for the PAS 2050 and *ILCD Handbook*, but remains adaptable for the dynamic LCA approach; (2) the temporal distribution of the sequestration, which is only accounted for in the dynamic LCA approach; and (3) the individual assessment of delayed emissions of all GHGs other than CO_2 using so-called dynamic characterization factors; in the PAS 2050 and *ILCD Handbook* a proxy is used by multiplying each GHG by its respective GWP_{100} before calculating the credit. The results in table 3 show that these differences can lead to opposite conclusions. Indeed, the best scenario according to both carbon footprint methods (PAS 2050 and ILCD) is not the same as that identified when using the dynamic LCA approach. Because it assesses the specific radiative forcing impact of every GHG flow (positive and negative emissions of any type of GHG from fossil and biogenic sources) on a consistent time frame, and because it allows decision makers analyzing the sensitivity of the conclusions to choose a time horizon, dynamic LCA is considered a preferable approach.

When to Account for the Sequestration of Carbon in Growing Trees

The results of the first case study show that the choice to consider biogenic carbon or its temporal distribution can significantly change the LCA results. Using dynamic LCA for the assessment of products containing biogenic carbon also raises the issue of temporal boundaries. The dynamic LCA conducted on one chair built at year 1 and burned at its end of life 50 years later shows very different results depending on whether the sequestration is assumed to occur before or after the chair is built (see figure 2).

For a time horizon of 100 years, the "before" scenario has a cumulative radiative forcing benefit (negative value) three times higher than the impact (positive value) of the "after" scenario. For a time horizon of 500 years, both scenarios have a negative cumulative radiative forcing; the "before" scenario has 4.3 times more forcing than the "after" scenario.

The methods that have been proposed to-date to account for temporary carbon storage (PAS 2050 and *ILCD Handbook*) do not consider the timing of the sequestration. The end-of-life biogenic CO_2 emissions have a zero impact (emissions − sequestration = 0), and a credit is given for storage related to the ratio of the storage time over the chosen time horizon. This gives a net negative impact. The results of the dynamic LCA show that the impact is very sensitive to the dynamics of the carbon sequestration (carbon balance curve) and to its timing (before or after the product is manufactured).

For the "after" scenario of this case study, it takes 270 years after the chair is built before the cumulative radiative forcing becomes negative, and it does so because we consider that a part of the sequestered carbon is permanently held in the soil. In the case where no carbon is sequestered in the soil, the impact would never become negative.

Because these results are very different for the "before" and "after" scenarios, the setting of an initial temporal boundary is both critical and informed by two opposing viewpoints. Choosing the "before" scenario means that one assumed the trees were grown to be used as a raw material. Choosing the "after" scenario means that one considers that nature provides some resources that can be used as raw materials; because wood is a renewable resource, a tree can be planted to replace the one that is cut.

Conclusion

There is currently no consensus regarding how to treat biogenic CO_2 in LCA. In this article we showed that not considering biogenic CO_2 can lead to biased conclusions. If a fraction of the biogenic carbon is assumed to be sequestered

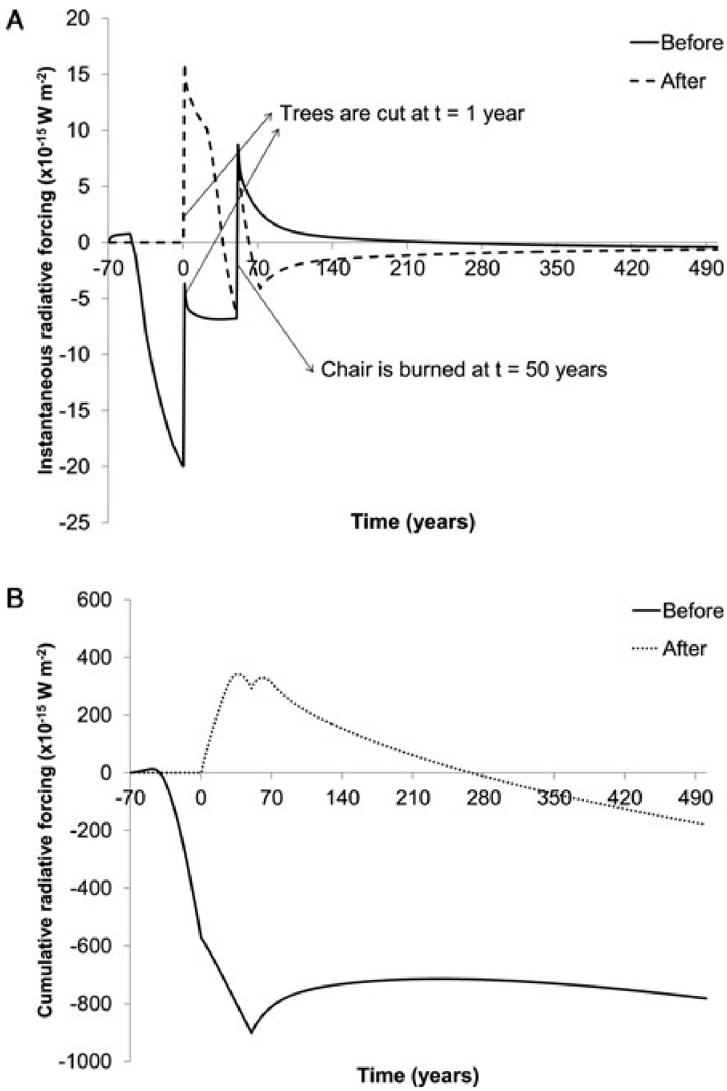

Figure 2 Instantaneous (a) and cumulative (b) radiative forcing determined using dynamic LCA, caused by one wooden chair for the incineration scenario with a sensitivity analysis done based on the timing of the sequestration (i.e., whether it occurs before or after the chair is built). W = watts.

permanently, as was the case for the carbon sequestered in the soil of the boreal forest or for 96.8% of the landfilled carbon, then the amount of biogenic carbon entering the product system is not equal to the amount leaving the system, which means that biogenic CO_2 emissions cannot be considered neutral. Also, as soon as a benefit is given for temporarily storing carbon, even if the total amount of biogenic carbon entering the product system is equal to the amount leaving the system, then it becomes important to account for the timing of every CO_2 flow that occurs in the life cycle inventory. Methodological inconsistencies otherwise lead to unreliable results. The dynamic LCA approach allows the consistent assessment of the impact, through time, of every GHG emission and sequestration, avoiding the necessity to artificially tag carbon flows as biogenic or fossil in origin.

Dynamic LCA also allows sensitivity testing of the results by time horizon. On an infinite time basis, there is no benefit to temporarily storing carbon or to delaying GHG emissions. Giving value to temporary climate mitigation is made possible by defining a time horizon beyond which we do not consider impacts, or by discounting, similar to what is done in economic decision making (Levasseur et al. 2012a).

The use of a discount rate to increase the importance of short-term emissions is still a controversial issue (Hellweg et al. 2003; Nordhaus 2007; O'Hare et al. 2009; Stern 2007), and is more a policy-based question than a scientific one, as is the choice of time horizon (Fearnside 2002; Moura-Costa and Wilson 2000). Given the debate concerning discounting and the fact that carbon footprint calculation methods do not use this type of time preference, we have decided to present the results without any discounting. However, it is possible for decision makers to apply a discount rate to annual dynamic LCA results like those presented in figure 1.

Choosing a finite time horizon for results analysis also provides a weight to time itself, and is a particular case (or a hidden way) of discounting, as emissions occurring after this time horizon are not considered (Hellweg et al. 2003). Generally 100 years is the preferred choice for a time horizon, as it is the reference time frame set for the Kyoto Protocol (UNFCCC 2008). However, as noted by the lead author of the chapter on radiative forcing of the IPCC First Assessment Report, there is no scientific argument that defends the choice of 100 years compared to other possible time horizons (Shine 2009). We have shown that the conclusions of a comparative LCA can change depending on the chosen time horizon for the analysis. In this respect, by making this choice transparent, dynamic LCA is a valuable approach for decision makers who have to understand the sensitivity of the conclusions when dealing with these kinds of choices.

The sensitivity analysis raises a new key issue regarding the use of time-differentiated carbon footprint and LCA methods: the setting of the temporal boundaries. Because the moment when each carbon flow occurs can significantly impact the results, it is important to pay attention to the assumptions made while defining temporal boundaries. Outside the proposed dynamic LCA method, none of the presented approaches considers this key issue. The decision regarding the timing of the sequestration of carbon in biomass relative to the moment the biomass is used is a kind of "chicken or egg" causality dilemma. The "before" scenario stands for the egg, as it is assumed that trees have been planted first with the objective of using them to build wood products. This scenario could be used, for instance, for specific afforestation projects of open woodlands where trees have been planted and then used as raw materials or energy sources. As for the "after" scenario, it stands for the chicken, as it is assumed that the forest is naturally there at first, exploited, and then trees are planted to renew the resource. This scenario could be used for wood coming from a sustainably managed forest.

Recent literature has highlighted the importance of considering biogenic CO_2, as well as the timing of GHG emissions in LCA and carbon footprint calculations. Because these assessments are increasingly used to guide policies and consumer choices, it is important that the methods used provide consistent and rigorous results. This article shows that dynamic LCA is the preferred approach to consistently assess the impact on global warming of any product or project. The analysis also leads to the conclusion that the results are sensitive to the different assumptions used while modeling the life cycle GHG flows, in particular those regarding forest management (carbon balance modeling) and the setting of temporal boundaries. To do away with the paradigm of biogenic CO_2 carbon neutrality improves the decisions made with LCAs in several cases, but increases the need for reliable data.

Acknowledgments

The authors acknowledge the industrial partners of the International Chair in Life Cycle Assessment (a research unit of CIRAIG [Interuniversity Research Centre for the Life Cycle of Products, Processes and Services]) for their financial support: Alcan, Arcelor-Mittal, Bell Canada, Cascades, Eco-Entreprises-Québec/Recyc-Québec, Groupe EDF/GDF-SUEZ, Hydro-Québec, Johnson & Johnson, Mouvement des caisses Desjardins, RONA, Total and Veolia Environnement.

Notes

1. One kilogram (kg, SI) ≈ 2.204 pounds (lb). Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference.
2. One watt (W, SI) ≈ 3.412 British thermal units (BTU)/hour ≈ 1.341×10^{-3} horsepower (HP). One square meter (m^2, SI) ≈ 10.76 square feet (ft^2).

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