Environ. Sci. Technol. **2010,** *44,* 3169–3174

Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments

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Received October 1, 2009. Revised manuscript received March 3, 2010. Accepted March 8, 2010.

The lack of temporal information is an important limitation of life cycle assessment (LCA). A dynamic LCA approach is proposed to improve the accuracy of LCA by addressing the inconsistency of temporal assessment. This approach consists of first computing a dynamic life cycle inventory (LCI), considering the temporal profile of emissions. Then, time-dependent characterization factors are calculated to assess the dynamic LCI in real-time impact scores for any given time horizon. Although generally applicable to any impact category, this approach is developed here for global warming, based on the radiative forcing concept. This case study demonstrates that the use of global warming potentials for a given time horizon to characterize greenhouse gas emissions leads to an inconsistency between the time frame chosen for the analysis and the time period covered by the LCA results. Dynamic LCA is applied to the US EPA LCA on renewable fuels, which compares the life cycle greenhouse gas emissions of different biofuels with fossil fuels including land-use change emissions. The comparison of the results obtained with both traditional and dynamic LCA approaches shows that the difference can be important enough to change the conclusions on whether or not a biofuel meets some given global warming reduction targets.

1. Introduction

Life cycle assessment (LCA) is a tool used for evaluating the potential environmental impacts of a product or service throughout its entire life cycle, from raw material extraction to end-of-life. One of the major advantages of this tool is that it avoids shifting burdens between life cycle stages or between different environmental issues (*1, 2*). However, LCA also has limitations, one of which is a poor accounting for time-related conditions (*3*).

1.1. Temporal Resolution in LCA. In life cycle inventory (LCI), all emissions for a given pollutant throughout the life cycle are typically added into a single aggregate emission. Then, in life cycle impact assessment (LCIA), the potential impacts of the aggregated LCI emissions are characterized (*1*). LCIA methods have been developed using natural science-based modeling to link the inventory results to the environmental problems they cause. Each of these LCIA methods provides characterization factors that linearly represent the contribution of a mass of a given pollutant to a specific impact category, such as global warming, acidification, human toxicity, etc. (*4*).

Inventory results represent aggregated mass loadings, as they are the sum of several amounts of pollutant emitted by different processes spread out in space and time (*5*). Because of the lack of temporal information, LCIA traditionally relies on restricted steady-state models, and this reliance is considered to be an important limitation of LCA because it decreases its accuracy (*2, 3*). Releasing a big amount of pollutant instantaneously generally does not have the same impact as releasing the same amount of pollutant at a small rate over several years.

This paper introduces the concept of dynamic LCA in order to improve the methodology regarding temporal issues. In a dynamic LCA, the temporal profiles of emissions are considered so that the LCI result for each emission is a function of time rather than a single number. Once a dynamic inventory is calculatedd, the LCIA characterization model is solved dynamically, i.e. without using steady-state assumptions, to obtain time-dependent characterization factors that depend on the moment when the pollutant is emitted. For this paper, we explored the temporal aspects of one particular impact category, global warming.

1.2. LCA and Global Warming Assessment. The current practice in LCA is to use global warming potential (GWP), adopted by the Intergovernmental Panel on Climate Change (IPCC), as a characterization factor for global warming impact assessment (*6*). GWP expresses the cumulative radiative forcing value caused by an emission of a unit mass of a given greenhouse gas (GHG) over a defined time horizon, relative to the equivalent value for CO_2. The mathematical expression of GWP is given by the following

$$GWP_i^{TH} = \frac{\int_0^{TH} a_i[C_i(t)\ \mathrm{d}t]}{\int_0^{TH} a_r[C_r(t)\ \mathrm{d}t]} \quad (1)$$

where *TH* is the chosen time horizon, *a* is the instantaneous radiative forcing per unit mass increase in the atmosphere, $C(t)$ is the time-dependent atmospheric load of the released gas, *i* is the released gas, and *r* is the reference gas, carbon dioxide. Both numerator and denominator of eq 1 are called Absolute Global Warming Potentials (AGWPs) (*7*). The CO_2 atmospheric load $C(t)$ following a pulse emission is given by the Bern carbon cycle-climate model, which predicts the fate of CO_2 emissions by considering carbon sink dynamics (*8*). For other GHGs, the time-dependent atmospheric load is given by a first-order decay kinetic equation. To determine the life cycle impact score for the global warming impact category in "kg CO_2 equivalent", the LCI results for each greenhouse gas are multiplied by their respective GWP.

The GWP value is very sensitive to the chosen time horizon, especially for short-lived GHGs. Figure 1 illustrates this sensitivity, comparing time-dependent radiative forcing for CO_2 and methane. Because methane has a short lifetime in the atmosphere (12 years (*7*)), its total greenhouse effect will occur during the first years following its emission, as opposed to CO_2, which is much more persistent (thousands of years). When the time horizon changes from 100 to 500 years, for example, the numerator in eq 1, represented by the area

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10.1021/es9030003
Published on Web 03/19/2010

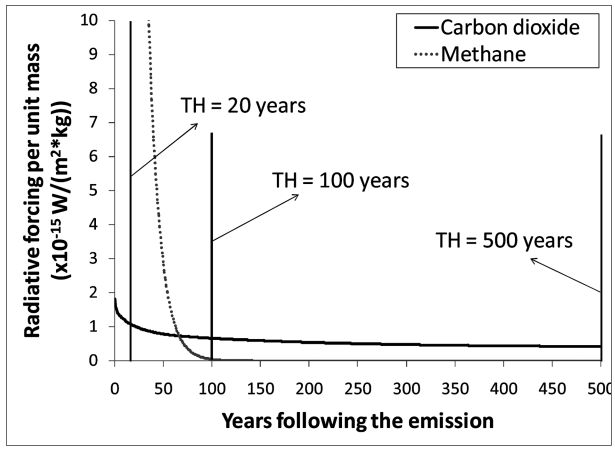

FIGURE 1. Radiative forcing of a unit mass pulse emission at time zero for carbon dioxide and methane with the three time horizons proposed by IPCC.

TABLE 1. GWP Values for CO_2, CH_4, and N_2O for Time Horizons of 20, 100, and 500 Years As Published by IPCC in the Fourth Assessment Report (*7*)

	20 years	100 years	500 years
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153

under the curve in Figure 1, remains constant for short-lived GHGs, while the denominator increases significantly. This is why GWP values for methane increase considerably with a decreasing time horizon, which defines the integration boundaries as shown in Table 1.

The selection of a time horizon is equivalent to giving a weight to time and is one of the most critical parts of carbon accounting processes (*9*). Indeed, the shorter the time horizon, the greater the importance given to the impacts closer in time, because impacts occurring after the defined time horizon are not considered. Most LCIA methods use 100 years as the time horizon for GWP. The use of a fixed time horizon for GWP in LCA results in an inconsistency between the time horizon chosen for the analysis in a given LCA study and the time period covered by the results, especially for long-lasting products or projects.

Figure 2 illustrates this inconsistency by using the example of a building with a 75-year lifetime. An LCA conducted on this building will take into account every pollutant released during the entire life cycle of the building, from its construction to destruction, including the use phase, which considers maintenance, heating and air-conditioning activities. During these 75 years, GHGs will be released and will generate an impact on climate. By choosing an impact assessment method that uses GWP with a time horizon of 100 years, one might think that this LCA study considers the global warming impacts over 100 years. However, that is not really the case. In fact, the impact of an emission which occurs 50 years after construction, for example, will be considered from year 50 to year 150. To be consistent with the 100-year time horizon chosen for the analysis, there is a need to develop characterization factors that account for a flexible time horizon to correctly represent the effect of the timing of the emissions. O'Hare et al. (*10*) also explain the problematic inconsistency in the treatment of time while using GWP indices.

When different products or scenarios are compared, it is important to make sure that the impacts are assessed based on the same temporal boundaries; otherwise there is a risk of biasing the results. Usually, an infinite time horizon is

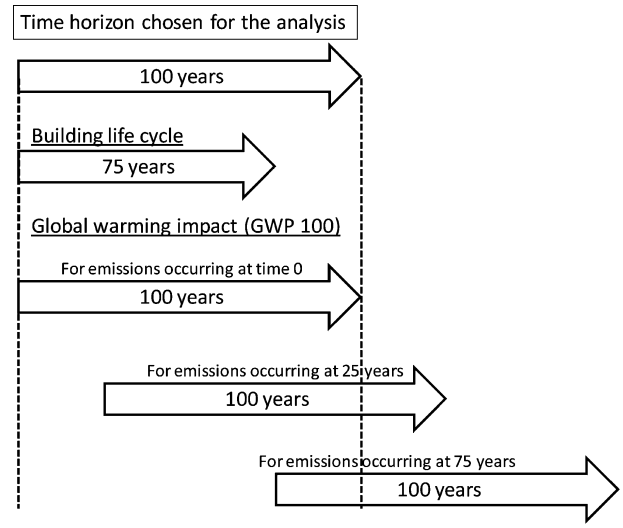

FIGURE 2. Illustration of the inconsistency in time frames for global warming LCIA with the example of a 75-year lifetime building.

used in LCIA to consider the total potential impacts and to avoid time preferences (*6*). Nevertheless, for some impact categories, such as global warming, choosing a finite time horizon results in an inconsistency between the time frame selected for the analysis and the time frame covered by LCIA results.

1.3. Life Cycle GHG Analysis of Biofuels. In recent years, growing concerns over global warming and fossil fuel depletion have led several countries to establish regulations regarding the development of biofuels (*11*). LCA is often used to compare different scenarios of replacement for fossil-fuels replacement with biomass-based fuels. These LCA results are useful in policy-making to determine whether or not a given fuel meets GHG reduction targets while considering the contribution of every life cycle stage. Intense debate continues over whether biofuels are the right alternative to petroleum fuels. Several studies have shown the benefits of replacing fossil fuels with biomass-based fuels (*12, 13*). However, the sustainability of this solution has been questioned by some researchers (*14*). One major issue pertains to considering the direct and indirect land-use change (LUC) emissions when accounting for GHGs from biofuels (*14, 15*).

With increasing biofuel demand, the amount of natural land required to grow biofuel feedstock crops (direct effects) or to produce the food needed to replace the biomass now used for biofuel production (indirect effects) is also increasing. These land transformations lead to GHG emissions (LUC emissions) caused by deforestation or removal of the existing vegetation, which occurs during the first years, and by the sacrificed sequestration potential of the natural land, lost for the following decades, which is equivalent to additional emissions (*14*).

The United States has set some GHG thresholds for biofuels under the 2007 Energy Independence and Security Act (EISA). To determine whether or not renewable fuels produced from different biomass feedstocks can meet these targets, the US EPA (*16*) has published a study as part of the proposed revisions to the National Renewable Fuel Standard Program (RFS2). In this study, GHG emissions produced over the entire life cycle of the renewable fuels, including LUC emissions, are compared to the life cycle GHG emissions for the average gasoline or diesel fuels used in 2005.

1.4. Prior Work and Objectives. Temporal aspects in carbon accounting are just emerging in the literature. The British Standards Institution (*17*), in its specification for the assessment of the life cycle GHG emissions of goods and

services, proposes a weighting factor to include the effect of the timing of the emissions in GHG accounting for life cycles with a long use phase. This factor is derived from a simplification of the Bern carbon cycle-climate model rather than from an exact mathematical solution and is only applicable to CO_2 emissions.

Two other papers address the particular problem of the timing of the emissions for biofuels studies while considering LUC emissions. O'Hare et al. (*10*) introduced a new metric named fuel warming potential (FWP), which is the ratio of the cumulative radiative forcing occurring over a given time horizon for the studied biofuel, relative to the same radiative forcing value for the petroleum fuel. They developed a model (BTIME) to compute this metric considering the timing of the fuels emissions and including land-use change, but it is only applicable to CO_2-equivalent factors (all emissions being previously converted using GWPs). Kendall et al. (*18*) proposed a time correction factor (TCF) to properly represent the impact of an initial CO_2 emission amortized over a defined time horizon, such as the initial LUC emission in the case of biofuels studies. TCFs have been computed for different time horizons and are applicable for pulse emissions amortized over a subsequent period of time; they cannot be used to assess different temporal profiles of GHG emissions. These two approaches are based on the concept of cumulative radiative forcing used by the IPCC for GWP development.

The dynamic LCA approach we propose here produces an impact score that is responsive to the chosen time horizon. Dynamic characterization factors are developed for the global warming impact category, based on the cumulative radiative forcing concept, for carbon dioxide and non-CO_2 GHGs and applicable to any type of temporal profile. The application of dynamic LCA is then illustrated building on the US EPA life cycle GHG analysis on renewable fuels.

2. Methodology

2.1. Development of Dynamic Characterization Factors for Global Warming. To develop dynamic characterization factors (DCFs) for global warming impact assessment, the same scientific models as for the calculation of GWP indices were used. The idea is to take the AGWP equation for each GHG and to integrate it continuously through time as shown in eq 2.

$$DCF_i(t)_{cumulative} = AGWP_i(t) = \int_0^t a_i[C_i(t)]\,\mathrm{d}t \qquad (2)$$

For carbon dioxide, as previously mentioned, the atmospheric load following a pulse emission $C(t)$ is given by the most recent Bern carbon cycle-climate model using a background CO_2 concentration of 378 ppm and can be expressed by eq 3 (*7*).

$$C(t) = a_0 + \sum_{i=1}^{3} a_i e^{-t/\tau_i} \qquad (3)$$

$$a_0 = 0.217,\ a_1 = 0.259,\ a_2 = 0.338,\ a_3 = 0.186$$

$$\tau_1 = 172.9 \text{ years},\ \tau_2 = 18.51 \text{ years},\ \tau_3 = 1.186 \text{ years}$$

For other gases, the atmospheric load following a pulse emission is given by a first-order decay equation where the inverse of the kinetic constant is the adjusted lifetime τ (*19*). Equation 4 illustrates the expression of the time-dependent atmospheric load for non-CO_2 GHGs.

$$C(t) = e^{-t/\tau} \qquad (4)$$

The adjusted lifetimes for the different GHGs (τ), the instantaneous radiative forcing per unit mass increase in the atmosphere for each gas (a_i), and the details concerning the feedback and indirect effects taken into account in the determination of these values are available in Forster et al. (*7*). The dynamic characterization factors obtained with this method represent the cumulative radiative forcing per unit mass of GHG released in the atmosphere since the emission and are shown in Figure 3a for carbon dioxide and methane. To obtain the instantaneous value of the characterization factor for any year following the emission, shown in Figure 3b, the time scale was divided into one-year time periods and the integration boundaries were set for every time step, as shown in eq 5.

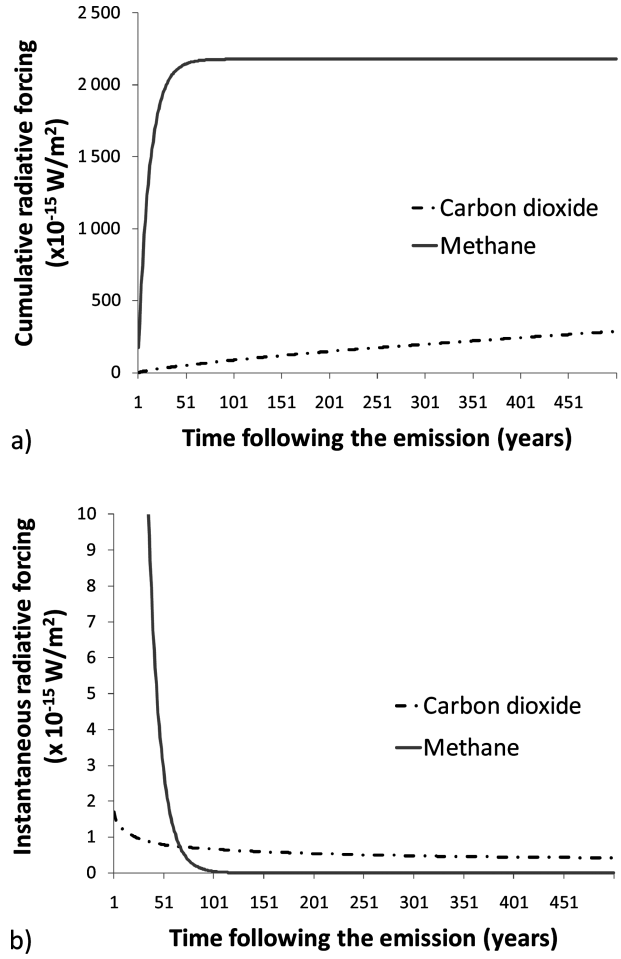

FIGURE 3. Time-dependent cumulative (a) and instantaneous (b) radiative forcing of a unit mass pulse emission at time zero for carbon dioxide and methane.

$$DCF_i(t)_{instantaneous} = \int_{t-1}^{t} a_i[C_i(t)]\,\mathrm{d}t \qquad (5)$$

Computing the time-dependent impact on global warming (GWI) for the considered life cycle is now possible by combining a dynamic inventory with yearly DCFs, using eq 6. The dynamic inventory for each GHG is obtained by dividing the life cycle in one-year time steps and by adding the different emissions of each GHG occurring at every time step

$$GWI(t) = \sum_i GWI_i(t) = \sum_i \sum_{j=0}^{t} [g_i]_j \cdot [DCF_i]_{t-j} \qquad (6)$$

where g is the inventory result, DCF is the instantaneous dynamic characterization factor, and i stands for every GHG present in the inventory. Equation 6 implies that to compute

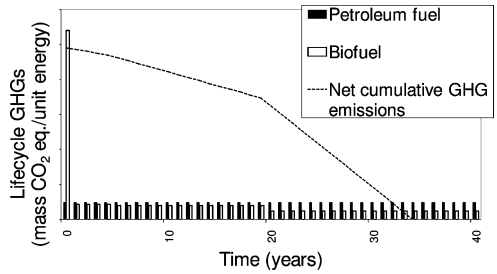

FIGURE 4. Comparison of GHG emissions per unit energy between a first-generation biofuel (corn ethanol) and gasoline with the net cumulative GHG emissions curve (dashed line), which shows the payback time for the biofuel to compensate the initial LUC emission [data from US EPA (*16*)].

the impact on global warming at a given time t caused by a given GHG i, we have to multiply the total emission (dynamic inventory result) occurring at time t by the DCF at time 0 (because this amount of GHG has just been released). We then add the score assigned to the total emission occurring at time t-1 multiplied by the DCF at time 1 (because it has been released one time step ago) and so on, until we finally add the total emission occurring at time 0, multiplied by the DCF at time t. The result provides the increase in radiative forcing at time t caused by every discrete GHG emission over the course of all the life cycle processes since the beginning of the life cycle.

2.2. Application to the US EPA Life-Cycle GHG Analysis on Renewable Fuels. In its study, the US EPA (*16*) takes into account the direct and indirect LUC emissions caused by the production of biomass as a renewable fuel feedstock. The time profile of LUC emissions is very different from that of fossil fuel and biofuel life cycles (*10*). LUC emissions are very important the first year because of the removal of existing vegetation. However, they drop below the direct fossil fuel emissions from year two, even though they are still present, albeit at a decreasing rate, for the following 80 years because of residual vegetation degradation and sacrificed sequestration potential of the natural land. As shown in Figure 4 for corn ethanol, GHG emissions per unit energy are higher for biofuel than for the displaced fossil fuel for the first year because of these LUC emissions. For subsequent years, life cycle GHG emissions are lower for biofuels than for petroleum fuels. As time goes by, the cumulative reduction in GHG emissions compensates for the initial LUC emissions and a payback time can be computed, which determines after how many years of fuel displacement the GHG balance becomes negative, i.e. better for biofuel than for fossil fuel use. This payback time does not account for the atmospheric residence time of GHGs, but only their different emission flows.

In the US EPA study (*16*), life cycle GHG emissions are computed for two petroleum fuels (average gasoline and diesel for the year 2005) and for different types of biofuel (corn ethanol from natural gas, coal and biomass dry mills, switchgrass and corn stover cellulosic ethanol, sugar cane ethanol, soy-based, and waste grease biodiesel). According to typical LCA practice, all the GHG emissions for a given fuel are multiplied by the corresponding GWP index for 100 years and then summed over a total impact score in "mass CO_2 equivalent per unit energy of fuel" for the entire fuel life cycle. Then, for the considered biofuels, the direct and indirect LUC emissions are added as a function of time to generate an emission profile as the one showed in Figure 4.

Once these results are obtained, an appropriate time horizon must be chosen for the analysis so as to compare a given biofuel to the petroleum-based fuel it replaces. For global warming mitigation projects where time is an important factor, such as in the case of substituting fossil fuels with biofuels while considering LUC emissions, the time horizon chosen for the analysis has a crucial impact on the estimated benefits of the project (*20*). Another critical decision in this analysis is whether or not to apply a discount rate to emphasize near-term versus longer-term emissions. Establishing a finite time horizon for result analysis already provides a certain weight to time and is a special case of discounting (*21, 22*). Since impacts occurring after the chosen time horizon are not considered, a shorter time horizon means that the impacts occurring earlier are more important than those occurring later. The importance given to short-term emissions can also be increased by using a discount rate similar to what is done in economic decision-making. The net present value (NPV) is then computed, as shown in eq 7, providing total values for both fuels that can be compared to determine the total GHG reduction caused by the use of the biomass-based fuel

$$NPV = \sum_{t=0}^{TH} \frac{GHG_t}{(1+r)^t} \tag{7}$$

where GHG_t is the total GHG emission for year t, r is the discount rate (which can be set to zero if no discount rate is applicable), and TH is the chosen time horizon.

The choice of a time horizon and the use of a discount rate is not a scientific decision but rather a policy-based one (*9, 23*). Hellweg et al. (*22*) concluded that discounting contradicts fundamental ethical values and should not be applied in LCA. Discounting in GHG accounting is the subject of several important debates (*10, 24, 25*). The decision to use or not use discount rates on dynamic LCA results is independent of the proposed approach and will not be discussed further in this paper. In the US EPA study, three different discount rates (0, 2, and 3%) and time horizons (30, 50, and 100 years) were used, and the method developed in this paper was applied using these values for comparison purposes.

For the application of dynamic LCA to US EPA data, we used life cycle emissions per unit energy for the three considered GHGs (CO_2, CH_4, and N_2O) for gasoline, corn ethanol (natural gas-fired dry mill), and corn stover cellulosic ethanol. Direct and indirect LUC emissions for corn ethanol were then added as a function of time to generate dynamic inventories. Equation 6 was then used to compute the instantaneous impact on global warming for the three fuels caused by their respective GHG emissions. Finally, eq 7 was used for the different time horizons and discount rates to get NPVs of the cumulative radiative forcing that occurred during the given time horizon. Ethanol's NPV is compared to the NPV of gasoline to obtain the relative change in GHG impacts expressed in percentage (percent impact change or % IC), as shown in eq 8, which can then be compared to the value obtained by the US EPA using the traditional LCA method.

$$\%IC_{ethanol} = \frac{(NPV_{ethanol} - NPV_{gasoline})}{NPV_{gasoline}} \times 100 \tag{8}$$

A positive result for eq 8 means that ethanol has a greater impact on global warming than gasoline, while a negative result indicates that ethanol leads to an impact reduction. These results can be compared with the Energy Independence and Security Act threshold, which is −20% for corn ethanol.

3. Results and Discussion

Figure 5 shows the results of the relative change in GHG impacts for corn ethanol obtained with both traditional and dynamic LCA approaches for three different time horizons and two discount rates.

The results show that dynamic LCA generates higher values for percent impact change, which means that corn

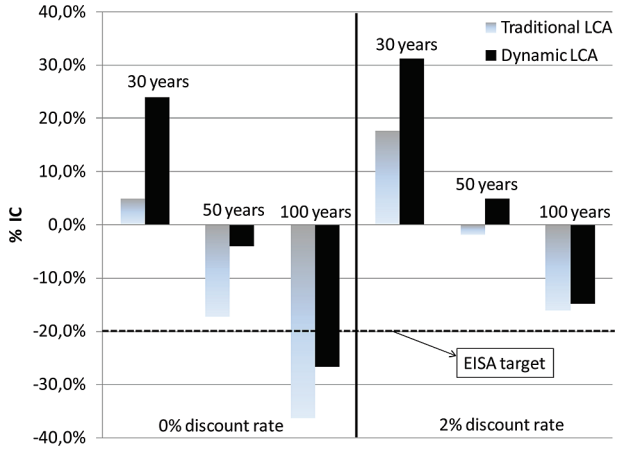

FIGURE 5. Comparison of the traditional and dynamic LCA methods for the relative change in GHG impacts (% IC) caused by the substitution of gasoline with corn ethanol (natural gas-fired dry mill) for time horizons of 30, 50, and 100 years with 0% and 2% discount rates.

ethanol is less favorable, compared to gasoline, than it was with the traditional LCA approach. Therefore, the lack of consideration for the temporal profile of the emissions in traditional LCA tends to underestimate the impact of LUC emissions. This is due to the fact that, in practice, the traditional LCA method uses fixed time horizons for GWP regardless of the moment when the emissions occur. But the residence time of early emissions is longer relative to a given target time, so the impact on radiative forcing of these emissions is greater (*10*). To consider the effect of the temporal profile of GHG emissions on atmospheric residence time, the later the emissions occur, the shorter the time horizon used for assessing their impact on global warming should be. The dynamic LCA approach uses characterization factors with variable time horizons to account for the atmospheric residence time of each GHG emission, which can change the results very significantly. As shown with the corn ethanol example, the bias in the results obtained with traditional LCA can be important enough to make authorities favor one type of biofuel that would have not been chosen with dynamic LCA because it would not have met the target set for GHG reductions.

Hence, the political choice of the time horizon is a key element, as it can make biofuel acceptable or not in respect to the given targets. In this case, with a 0% discount rate, corn ethanol would meet the −20% target with a time horizon of 100 years; however, this would not be the case for a time horizon of 30 or 50 years. For a 0% discount rate, the minimum value for a time horizon in which corn ethanol would meet the −20% target is 54 years. For a time horizon of 100 years, the maximum discount rate for which corn ethanol meets the target is 1.6%.

The dynamic characterization factors proposed in this paper for global warming impact assessment follow basically the same approach as the FWP metric proposed by O'Hare et al. (*10*). The experts of the panel that peer reviewed the US EPA study (*26*), although generally agreeing with the approach, noted that the main limitations were the lack of consideration for non-CO_2 GHGs and the absence of variability for the instantaneous radiative forcing and the time-dependent atmospheric load. In this study, we went a step further by developing dynamic characterization for non-CO_2 GHGs. The major concern about the accuracy of the radiative forcing expressions used in this paper and in the other approaches mentioned lies in the variability of the instantaneous radiative forcing and the time-dependent atmospheric load [a_i and $C(t)_i$ in eq 1] with the background atmospheric concentration (*27*). To simplify the approach, the IPCC uses constant background concentrations to develop GWP indices for all GHGs; however, this is unrealistic because GHG concentrations are constantly increasing and will continue to do so (*28*). Also, the relationship between the radiative forcing expressed with GWP and the real impact on climate is complex and probably nonlinear (*29*).

Another important advantage of the dynamic LCA approach developed in this paper is its applicability to any temporal profile of the emissions and to any different type of LCA studies. Moreover, this dynamic LCA approach is not applicable only to a specific impact category. It allows the calculation of real-time impacts of any product system for any impact category by developing further sets of dynamic characterization factors.

For the global warming impact category, results can be biased in traditional LCA and dynamic LCA can improve accuracy. The dynamic LCA approach also has the asset of providing temporal information to the practitioner, which traditional LCA cannot. It can be particularly useful for assessing the implications of the choice of different time horizons in decision making (*9*).

Other types of applications related to climate change can also benefit from the dynamic LCA approach, including the study of global warming mitigation scenarios by temporary carbon sequestration. In afforestation and reforestation projects, the dynamics of sequestration significantly influence the temporal profile of the global warming impact, and therefore it is crucial to account for time frame in order to properly assess any proposed projects (*30*). Several issues surrounding carbon sequestration projects are still being debated (for example, what happens when projects end, when and how to give credits for the sequestered carbon, etc. (*20*)). The approach developed in this paper could be a useful tool to address these issues.

Acknowledgments

The authors acknowledge the reviewers for their constructive comments which allowed to improve the quality of this paper and the financial support of the industrial partners of the International Chair in Life Cycle Assessment (a research unit of CIRAIG): 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.

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