Instruction Manual

New Generation Carbon Footprinting

thanks to the Dynamic carbon footprinter

V1.0

Acknowledgements

Production

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Author

Annie Levasseur, CIRAIG

Supervision and support

Pascal Lesage, Manuele Margni and Réjean Samson, CIRAIG

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1. ABC's of dynamic LCA for global warming

Dynamic life cycle assessment for global warming aims at assessing the impact of life cycle greenhouse gas (GHG) emissions on radiative forcing considering the moment when these emissions occur.

1.1 Limitations of current LCA methodology

Current LCA methodology does not consider when emissions occur. In the inventory phase, all the emissions of a given pollutant are summed into a single aggregated value. The global warming impact of this aggregated emission is then assessed by multiplying it by its global warming potential (GWP) for a given time horizon (20, 100 or 500 years). Finally, the life cycle impact for the global warming category in kg CO_2-eq is given by the sum of the impact of each GHG (see Figure 1).

GHG_1 impact

$$[E_1(GHG_1) + E_2(GHG_1) + \ldots + E_y(GHG_1)] \times GWP\,100\,(GHG_1)$$

$$+$$

GHG_2 impact

$$[E_1(GHG_2) + E_2(GHG_2) + \ldots + E_y(GHG_2)] \times GWP\,100\,(GHG_2)$$

$$+ \quad \vdots \quad =$$

$$+$$

GHG_x impact

$$[E_1(GHG_x) + E_2(GHG_x) + \ldots + E_y(GHG_x)] \times GWP\,100\,(GHG_x)$$

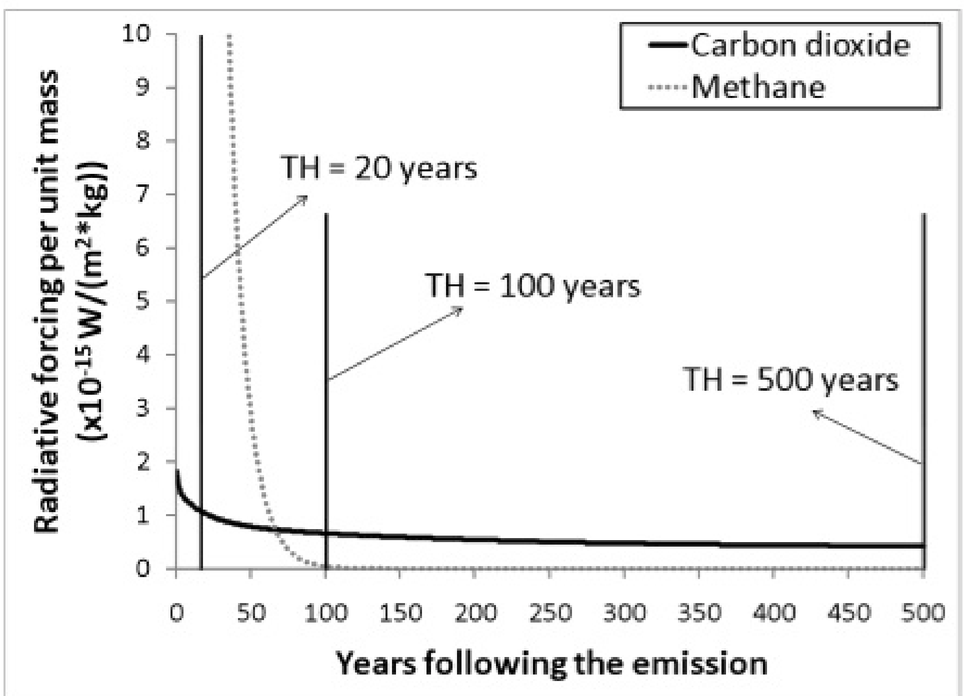
Total impact
Kg CO_2 -eq

Figure 1. Global warming impact assessment with current LCA methodology for a 100-year time horizon. GHG_1 to GHG_x stand for each greenhouse gas identified by the IPCC and E_1 to E_y stand for the different emission sources.

GWPs have been proposed by the Intergovernmental Panel on Climate Change (IPCC) which provide the cumulative radiative forcing caused by a pulse-emission for a given GHG over a given time horizon, divided by the same value calculated for CO2 (see Equation 1).

(1)
$$GWP_i^{TH} = \frac{AGWP_i^{TH}}{AGWP_{CO_2}^{TH}} = \frac{\int_0^{TH} a_i \left[C_i(t)\right] dt}{\int_0^{TH} a_{CO_2} \left[C_{CO_2}(t)\right] dt}$$

where AGWP is the absolute global warming potential, TH is the time horizon, i stands for the GHG for which GWP is calculated, a is the instantaneous radiative forcing per unit mass of GHG in the atmosphere and C(t) is the time-dependant GHG atmospheric load following a unit mass pulse-emission. The GWP calculation for methane and CO2 is shown in Figure 2 as an example.



GWP (kg CO_2-eq/kg)	20 years	100 years	500 years
CO_2	1	1	1
Methane	72	25	7.6

AGWP ($W.yr.m^{-2}.kg^{-1}$)	20 years	100 years	500 years
CO_2	$2.47x10^{-14}$	$8.69x10^{-14}$	$2.86x10^{-13}$
Methane	$1.78x10^{-12}$	$2.17x10^{-12}$	$2.17x10^{-12}$

Figure 2. GWP is determined by the area under the curve for the GHG for which GWP is calculated, between zero and the chosen time horizon, divided by the area under the CO2 curve for the same time period (Levasseur et al. 2010).

The lack of consideration for the temporal distribution of GHG emissions in current LCA methodology leads to two different issues:

1) an inconsistency in temporal boundaries
2) the inability to assess the impact of temporarily storing carbon or delaying GHG emissions.

The first issue is inherent to using GWPs for a fixed time horizon. Indeed, by choosing a 100-year time horizon for GWPs, one considers only the radiative forcing occurring during the 100 years following the emission to assess. Therefore, for an LCA conducted on a relatively long-term product system, e.g. for a building with a 75-year lifetime (see Figure 3), the GHG emissions caused by the construction (year 1) are assessed over the first 100 years, while the GHG emissions caused by its end-of-life (year 75) are assessed over a time period from 75 to 175 years following the construction. If LCA results from two products or projects with different temporal profiles are compared, the time frame over which the global warming impact is calculated would not be the same for both systems. To compare products or projects consistently, one must use a flexible time horizon to assess the impact of each GHG emission, which would begin when the emission occurs and would finish at the end of the time horizon chosen for the analysis.

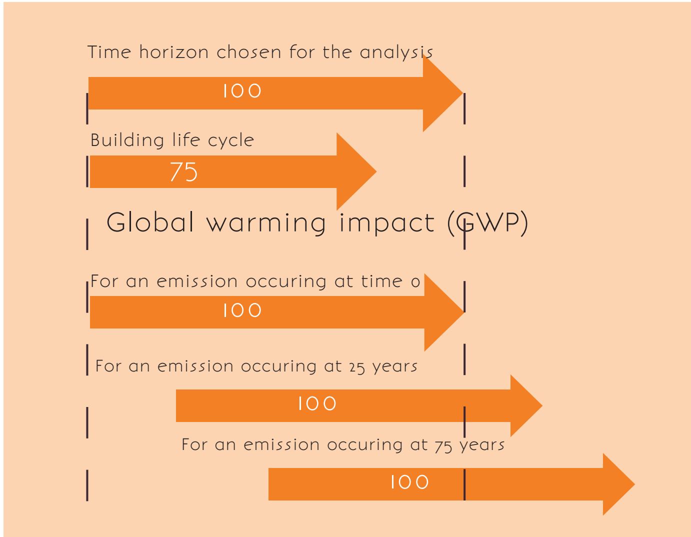


Figure 3. Illustration of the inconsistency in temporal boundaries while assessing global warming impact with GWP for a fixed time horizon with the example of a building life cycle with a 75-year lifetime (Levasseur et al. 2010).

The second issue is related to the lack of consideration for the timing of the emissions in life cycle inventory. If one wants to give a value to temporary carbon storage, e.g. for a long-life wooden product, the use of current LCA methodology will give a zero result, since the amount of carbon sequestered by the trees will be substracted to the (same) amount of carbon released at the product's end-of-life. Temporary carbon storage has a value if and only if a time horizon is chosen, over which impacts are calculated, so that delayed emissions have a lower impact over this time period, which current LCA methodology cannot evaluate.

1.2 Dynamic LCA approach

Dynamic LCA takes into account the temporal distribution of the emissions using a dynamic inventory. The life cycle is divided in one-year time steps and the amount of pollutant released is determined for each year and each GHG. This dynamic inventory is then assessed with dynamic characterization factors (DCF), which consist in the integral of the radiative forcing expression (AGWP) for every time step (see Equation 2).

(2) $$DCF_i(t)_{instantan\acute{e}} = \int_{t-1}^{t} a_i\left[C_i(t)\right]dt$$

This equation allows determining the atmospheric radiative forcing [W.m-2.kg-1] t years after the emission of 1 kg of GHG i. The impact on radiative forcing (GWI) caused by the life cycle emissions can then be calculated at any t time using Equation 3 where $[g_i]j$ is the inventory result for GHG i at time j.

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

The cumulative impact on radiative forcing can be calculated at t time summing the instantaneous impact GWI of the previous years.

Dynamic LCA allows calculating the radiative forcing impact of the life cycle GHG emissions at any time, which enables to analyze the global warming impact of different scenarios where time is prevalent, such as temporary carbon storage, gradual carbon sequestration in biomass, delaying GHG emissions, etc. Moreover, dynamic characterization factors use a flexible time horizon to consistently assess GHG emissions over a given time frame.

Global warming impact assessment results are very sensitive to the choice of a time horizon. Usually, in LCA as in other carbon accounting or footprinting methods, the time horizon is chosen before the calculation is completed. Dynamic LCA provides the evolution of the global warming impact over time, which allows decision makers to test the sensitivity of the results to the choice of a time horizon.

The dynamic LCA approach, its assets and limitations, along with an example of application have been published in Environmental Science & Technology (Levasseur et al. 2010): http://pubs.acs.org/doi/abs/10.1021/es9030003.

2. Dynamic LCA calculation tool for global warming

A calculation tool (Excel file) has been developed to facilitate the application of the dynamic LCA approach. All cells, except those for which the user must enter data, are protected and cannot be modified. However, the tool is transparent and the content of each cell is visible. It is also possible for the user to copy the results and to paste them in another Excel file. The "Instructions" sheet provides basic guidelines for using the tool. It is important to set the Excel calculation option in manual as soon as the file is open, so that the tool will not recalculate each time a data is entered.

The only data that must be entered by the user is the dynamic inventory data ("Inventory" sheet). Emissions in kg for each GHG and for each life cycle year must be entered. GHGs can have different names for the same molecule. Line 1 shows the names used in the IPCC report in Table 2.14 (Forster et al. 2007). When another name is widely used, it is provided in line 2.

To develop a dynamic inventory, temporal boundaries must be defined in addition to the usual system boundaries, which determine which processes will be considered in the inventory. The first thing to do is to set the initial time limit (time zero), i.e. the moment when the first life cycle emission occurs. Then, the user must determine when each emission occurs relative to this initial time. As the time scale is divided into one-year time steps, the user must determine how many years there are between the emission and time zero, and enter the amount emitted on the corresponding line. All the emissions, from fossil or biogenic sources, must be entered. The amounts of CO_2 sequestered by the biomass must be entered as negative emissions. When there is no emission for a given GHG on a given year, the value "0" must be entered in the appropriate cell.

Figure 4 shows an example of a very simple dynamic inventory for a building life cycle. A complete example for the application of dynamic LCA, including dynamic inventory development, is also shown in section 3.

Temporal boundaries:
Construction emissions for year 1;
Heating emissions divided over 75 years;
Demolition emissions at year 75.

Inventory data (per building)

	Construction	Heating	Demolition
CO_2 (kg)	50 000	800 000	1000
CH_4 (kg)	100	1 500	1
N_2O (kg)	2	25	0.001

Dynamic inventory

	CO_2 (Kg)	CH_4	N_2O (Kg)
Year 1	50 000 + 800 000/75	100 + 1 500/75	2 + 25/75
Year 2 to 74	800 000/75	1 500/75	25/75
Year 75 to 100	1 000 + 800 000/75	1 + 1 500/75	0,001 + 25/75

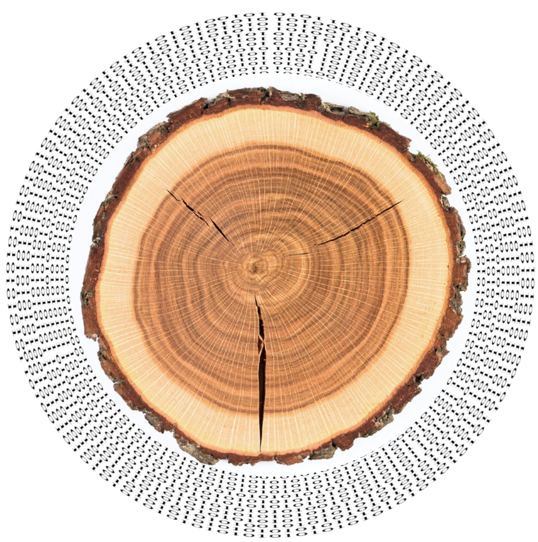
Figure 4. Development of a dynamic inventory for a simple life cycle (three aggregated processes, three GHGs) for a building with a 75-year lifetime.

Once the dynamic inventory is entered, the user must click the « Calculate » button on the « Results » sheet. The calculation can take some time (from a few seconds to a few minutes). Three types of results are provided in the "Results" sheet, available in numerical and graphic forms.

The instantaneous impact $GWI_{inst}(t)$ [W.m-2] is the radiative forcing caused by the life cycle GHG emissions at any t time following the initial time limit, i.e. the moment when the first emission occurs. A positive value means that the radiative forcing is higher that it would have been without the life cycle GHG emissions. A negative value means the opposite, i.e. the life cycle has a beneficial impact on global warming, decreasing radiative forcing. The instantaneous impact shows changes over time in radiative forcing, which is not possible when using GWP.

The cumulative impact $GWI_{cum}(t)$ [W.m-2] is the sum of the instantaneous impacts from time zero to time t. In other words, it is the total amount of additional radiative forcing caused by GHGs since the first life cycle emission. The cumulative impact allows comparing scenarios and determining which one has a higher impact on radiative forcing for any time horizon.

Finally, the relative impact $GWI_{rel}(t)$ [kg CO_2-eq] is the ratio of the life cycle cumulative impact over the cumulative impact of a 1 kg CO_2 pulse-emission at time zero. The relative impact transforms the dynamic LCA result into the same units as a current LCA, i.e. relative to a 1 kg CO_2 pulse-emission, while taking into account the timing of the emissions, which cannot be done while using GWPs.



3. Application example

Planting trees to mitigate GHG emissions caused by air travel

The following hypothetical example demonstrates how to use the calculation tool to conduct a dynamic LCA for global warming. The goal of this LCA is to assess the impact of a reforestation project to mitigate GHG emissions.

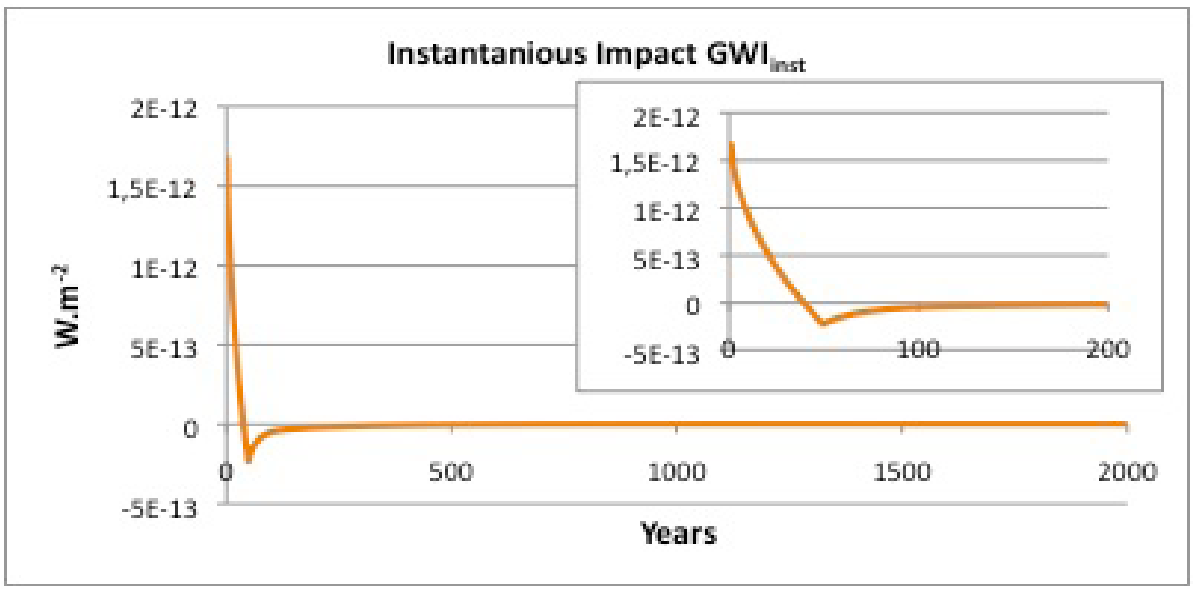
To mitigate a one-ton CO_2 emission from air travel, a passenger gives a certain amount of money to a reforestation project. Trees are planted and will grow during the following 50 years, at the end of which they are going to have sequestered one ton of CO_2 from the atmosphere. An assumption is made to determine the carbon sequestration dynamics: trees sequester carbon at a constant rate during their growth (which is not the case in reality). An LCA has been performed for the reforestation activities (sowing, seedling, transportation, etc.) and the results for the three principal GHGs, scaled-up to the number of trees needed to mitigate a one-ton CO_2 emission, are: 3 kg CO_2, 0,04 kg CH_4 and 0,001 kg N_2O. Finally, it is assumed that, at the end of the 50 years, there are no more flows between the atmosphere and the trees (no sequestration, no emission) and that the trees remain there forever (no wildfire, no forest exploitation).

The first thing to do is to define temporal boundaries. The initial time is the moment when the one-ton CO_2 emission caused by the airplane occurs. The emissions caused by the reforestation activities occur during the first year. The amount of CO_2 sequestered by the trees is divided equally over 50 years (20 kg per year). Table 1 shows the dynamic inventory to use in the calculation tool.

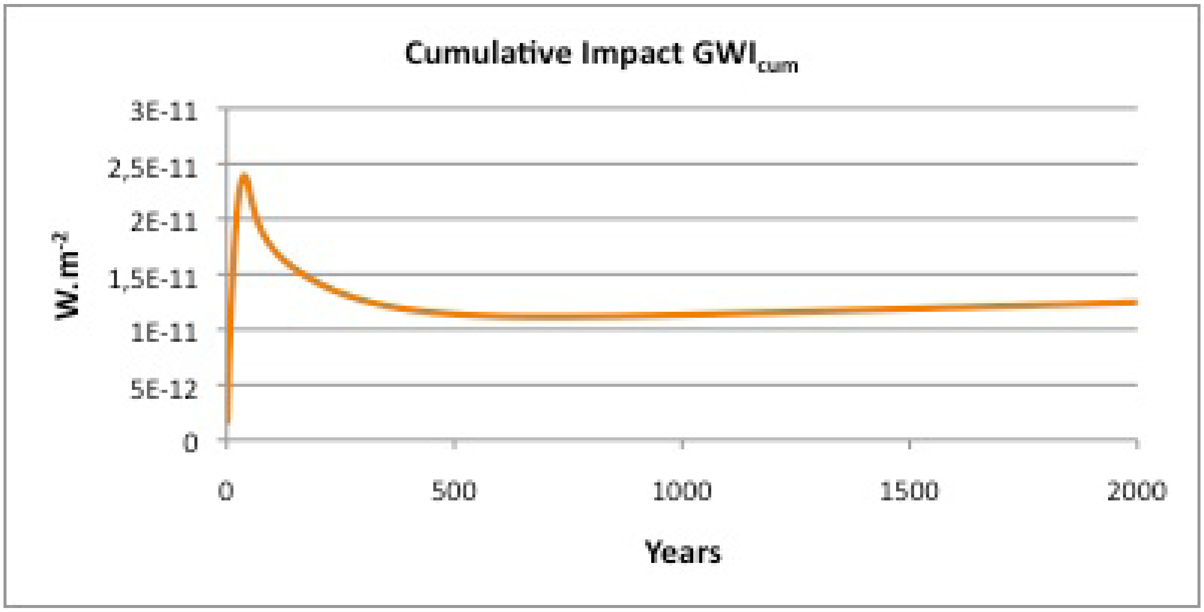
Table 1. Dynamic inventory for the example of the reforestation project to mitigate a one-ton CO_2 emission caused by air travel.

	CO_2 (kg)	CH_4 (kg)	N_2O (kg)
Year 1	1000 + 3 – 20 = 983	0.04	0.001
Year 2 to 50	-20	0	0
Year 50 and +	0	0	0

Figure 5 shows the results obtained with the calculation tool from the dynamic inventory presented in Table 1.



a)



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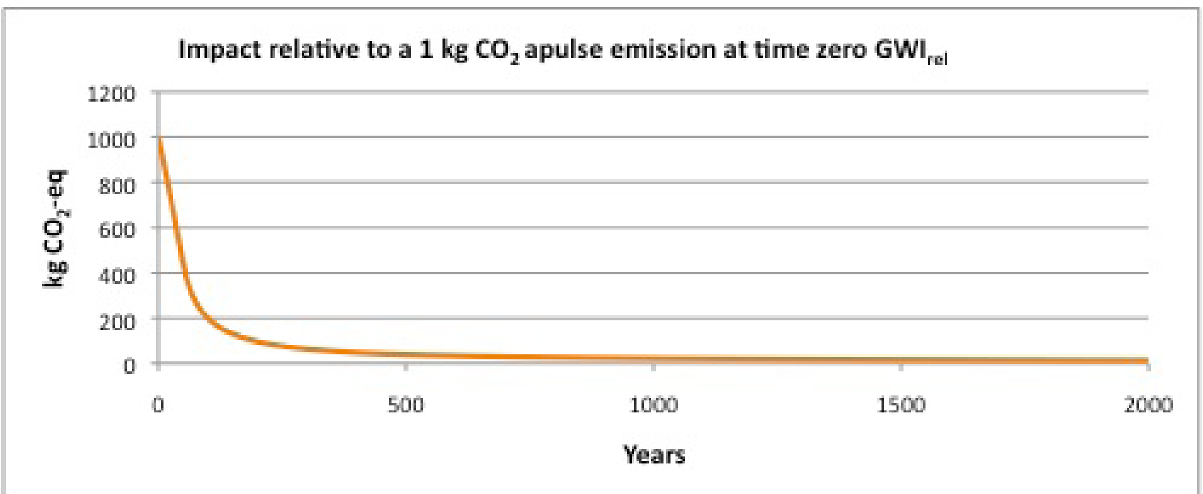

c)

Figure 5. Results of the dynamic LCA provided by the calculation tool for the example of a reforestation project to mitigate a one-ton CO_2 emission from air travel.

For comparison purposes, the current LCA methodology (see Figure 1) is applied to the inventory shown in Table 1 for a 100-year time horizon. The result is the sum of each aggregated GHG emission (3 kg de CO_2, 0.04 kg de CH_4 and 0.001 kg de N_2O) multiplied by its corresponding GWP100 (respectively 1.25 and 298 kg CO_2-eq/kg), which gives an impact on global warming of 4.3 kg CO_2-eq.

Since the amount of CO_2 sequestered by the trees is the same as the amount of CO_2 released by the airplane (1 ton), applying the current LCA methodology to this example gives the same result as an LCA performed on the reforestation activities. However, since the sequestration occurs gradually over a period of 50 years, while the total amount of CO_2 to mitigate is released at time zero, the impact on radiative forcing for the first decades is important, and then decreases to zero as shown by the instantaneous result (see Figure 5a).

The relative impact allows comparing the dynamic LCA results with those obtained from the current LCA methodology. As shown in Figure 5c, the time horizon needs to be of several centuries before the relative impact becomes equivalent to the current LCA result.

This example shows the benefits of using a dynamic LCA approach. As results are obtained for any time, the user can easily test the sensitivity of the results to the choice of a time horizon. Dynamic LCA is also a flexible approach, as it can be applied to any type of product or project, while considering consistently and rigorously the timing of every life cycle GHG emission.

4. References

Forster, P. et al. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In S. Solomon et al. (Ed.), Climate Change 2007: The Physical Science Basic. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 129-234). Cambridge, United Kingdom and New-York, NY, USA: Cambridge University Press.

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering time in LCA: dynamic LCA and its application to global warming impact assessments. Environmental Science & Technology, 44(8), 3169-3174.

INFORMATION

CIRAIG
École Polytechnique de Montréal
2900 Édouard-Montpetit
Montreal (Québec)

Contact Annie Levasseur
Phone : +1 514 340-4711 extension 4794
Email : annie.levasseur@polymtl.ca
Web site : www.ciraig.org