Integrating GHG dynamics in biomass-based products LCA

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Introduction

Time dimension is a crucial element of the climate change challenge. Climate dynamics imply indeed very inertial phenomena and GreenHouse Gases (GHG) lifetimes can vary from years to centuries [1]. Each work dealing with climate change requires a special convention or hypothesis about time: Global Warming Potentials (GWP) from the Intergovernmental Panel on Climate Change (IPCC) consider cumulative impacts of GHG emissions over a time horizon of 20, 100 or 500 years [1]; GHG emissions valuation highly depends on the chosen discount rate for marginal damage costs methods and on the selected emission scenario objective for marginal abatement costs methods [2, 3].

Life-Cycle Assessments (LCA) also need a discount rate hypothesis because they aggregate different timescales. An industrial product LCA for instance deals with production impacts, generally proportional to the functional unit, and with facilities impacts, such as equipments and buildings impacts. The common assumption is thus to share out these impacts with a 0% discount rate over the facilities lifespan, usually 20 years. Fortunately facilities impacts are often negligible compared to production impacts, so that this hypothesis influence is generally not significant.

Biomass production imply very different timescales: GHG fluxes can be occasional (deforestation), recurrent (savings) or extended (carbon sequestration or emission from soils). The first case study of this work, dealing with a biofuel LCA involving a land-use change, will show the significance of this last type of flux for the GHG impact results. The carbon neutral assumption of biomass emissions, widely stated in the LCA community, also introduces a bias in GHG accounting since it neglects carbon sequestration effects [4]. The second case study of this work will consider the carbon sequestration credit which could be granted to wood-based materials.

These difficulties about time dimension in climate change impact assessment raises the question of a temporal weighting of GHG emissions: for example, is it preferable to save 3 tCO_2 now or 5 tCO_2 in ten years? This work aims at answering such questions by defining GWP depending on the emission year, in line with the IPCC calculations. The interest of the resulting dynamic GWP will then be shown in the two case studies.

Definition of the dynamic Global Warming Potential

The IPCC defines the Global Warming Potential GWP_i of a component i as follows:

$$GWP_i = \frac{\int_0^{T_H} a_i \cdot C_i(t)\,dt}{\int_0^{T_H} a_{CO_2} \cdot C_{CO_2}(t)\,dt} \tag{1}$$

where T_H is the time horizon, usually 20, 100 or 500 years, a_i is the radiative efficiency of component i stated in $W.m^{-2}.ppm^{-1}$ for CO_2 and in $W.m^{-2}.ppb^{-1}$ for other GHG, and $C_i(t)$ is the time-dependent abundance of component i in the atmosphere after a pulse emission of this compound [1]. The radiative efficiency and the abundance function depend on the atmosphere composition and thus on the emission year since the atmosphere changes due to anthropogenic emissions. These phenomena will however not be considered in this preliminary work: radiative efficiencies will be taken as constants and the abundance function shapes as independent of the emission year.

By definition GWP takes into account all GHG effects on the radiative balance of the atmosphere within the time horizon frame and none of them beyond. The fundamental principle of the definition of dynamic GWP is to follow this convention. So the GWP of a compound i emitted at the year T_E will not consider its radiative effects after the time horizon:

$$GWP_{i,\ emitted\ at\ t=T_E} = \frac{\int_{T_E}^{T_H} a_i \cdot C_i\left(t - T_E\right)\, dt}{\int_0^{T_H} a_{CO_2} \cdot C_{CO_2}(t)\, dt} \tag{2}$$

Figure 1 presents this reasoning for CO_2 and a time horizon of 100 years. Equation (2) means graphically that the GWP of CO_2 emitted at T_E = 50 years is the ratio between the grey and black hatched areas.

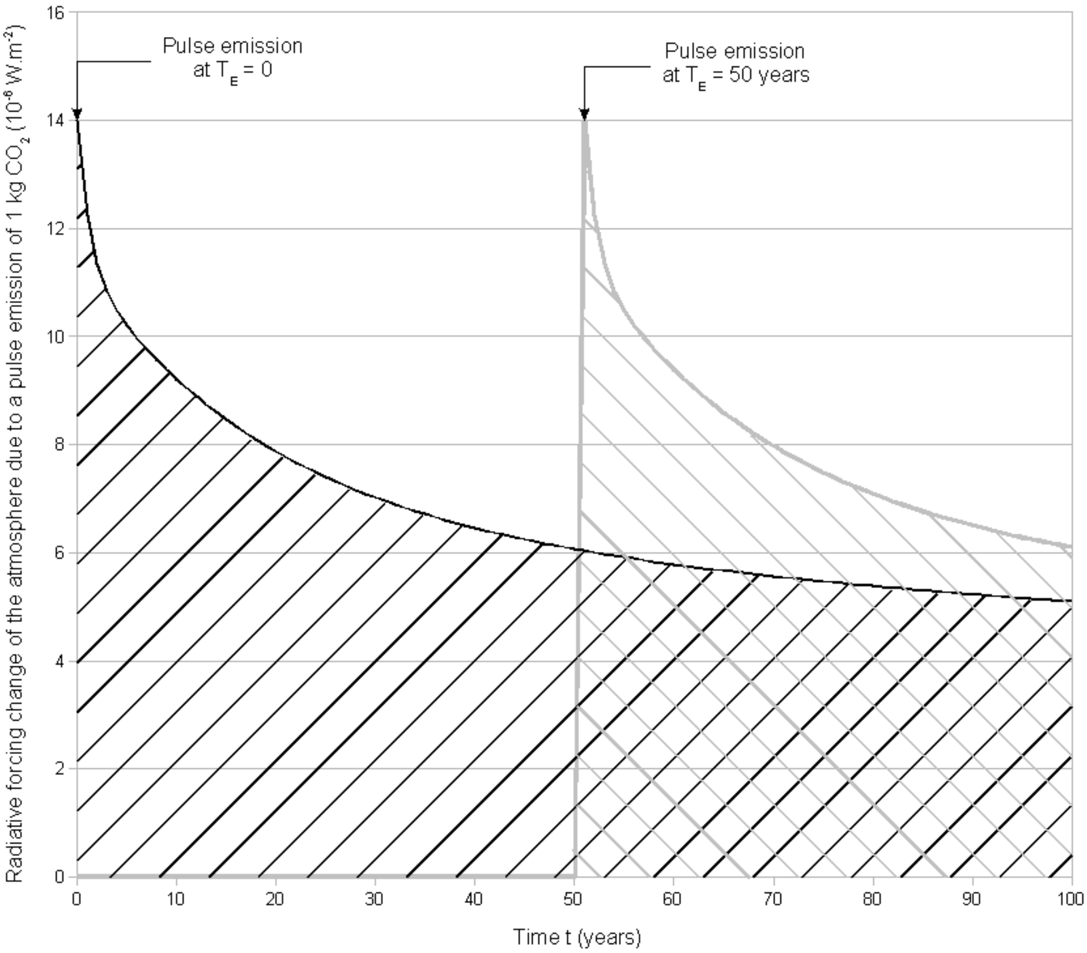

Figure 1: Definition of the dynamic GWP of CO_2 emitted at T_E = 50 years

Table 1 gives the resulting dynamic GWP per decade of carbon dioxyde CO_2, methane CH_4 and nitrogen dioxide N_2O for a time horizon of 100 years, resulting from equation (2) and IPCC data [1, 5].

Table 1: Dynamic GWP of CO_2, CH_4 and N_2O for a time horizon of 100 years

Emission year		**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Dynamic GWP ($kgCO_{2-eq}$ / kg)	CO_2	1	0.92	0.84	0.76	0.68	0.59	0.50	0.39	0.28	0.16	0
	CH_4	25	25	25	25	25	25	24	23	20	14	0
	N_2O	298	279	257	234	209	181	151	118	82	43	0

As a result of their definition, dynamic GWP are equal to 0 $kgCO_{2-eq}$ after the time horizon. Before this limit the decrease of GWP over years depends on the compound lifetime. Dynamic GWP of CH_4 for instance only decrease significantly in the last two decades due to its very short lifetime of 12 years. The results of table 1 finally allow to answer the introduction question whether it is preferable to save 3 tCO_2 now or 5 tCO_2 in ten years: an emission of 5 tCO_2 in ten years represent 5 x 0.92 = 4.6 tCO_{2-eq} and so should be preferable to save than 3 tCO_2 now.

Case study 1: Biofuel LCA involving a land-use change

A land-use change implies a carbon loss or uptake. Two types of carbon stock have to be considered: carbon from aboveground biomass and soil carbon. Both stocks depend on the land-use; for instance in Ile-de-France, the French region surrounding Paris, it has been estimated that one hectare of forest and of cereal crop typically represents, respectively, 80 and 6 tC for the aboveground biomass and 100 and 60 tC for the organic carbon in the first meter of soil [6]. If a land undergo a use change, these stocks are modified over a period of time depending on the change: if aboveground carbon losses (deforestation) are usually immediate, aboveground uptakes (reforestation) and soil carbon losses and uptakes occur over decades.

The objective of this first simplified case study is to compare these carbon fluxes to the GHG savings due to a biofuel production. The compared scenarios are shown in figure 2: in system B wheat ethanol is produced from one hectare of agricultural land, which is a grassland in the reference system A, and replaced an equal amount of energy from gasoline. In order to avoid allocation issues and make the LCA simpler, by-products from ethanol production were assumed to be burnt for energy purposes within the process.

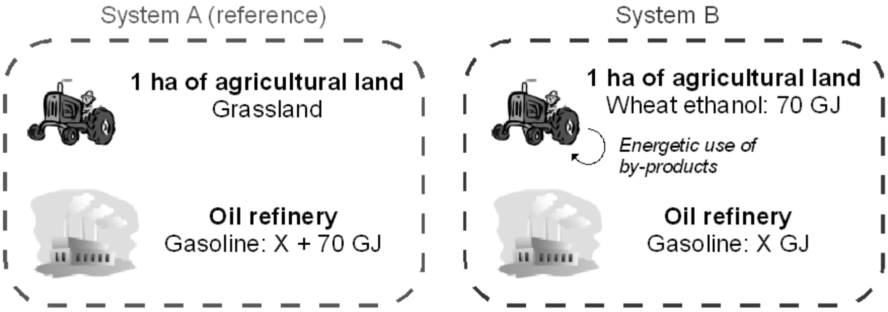

Figure 2: System definition of the compared scenarios, for 1 year, of the first case study LCA

LCA results needed came from the 2007 Joint Research Centre study and are valid for the European Union in 2010-2020 [7]. According to this study the production and use of 1 MJ of wheat ethanol emits 32 gCO_2, 0.07 gCH_4 and 0.06 gN_2O in the system B conditions; the production and use of 1 MJ of gasoline emits 83.9 gCO_2. Using standard GWP from the fourth assessment report of the IPCC for a time horizon of 100 years (see values in table 1, emission year 0), wheat ethanol production so saves 33.2 $gCO_{2\text{-eq}}$ / MJ produced or 2.32 $tCO_{2\text{-eq}}$ / ha / yr in the case of no land-use change.

In French conditions, substitution of a grassland by an annual crop may lead to a soil carbon loss of 92 ± 12 $tCO_{2\text{-eq}}$ in 50-60 years, of which 75% in the first 20 years. Figure 3 presents the GHG impact over 100 years of the substitution of system A by system B, combining the annual saving due to replacement of gasoline by ethanol, assumed as constant, and the dynamic carbon loss due to land-use change. GHG are aggregated using the standard GWP from the IPCC.

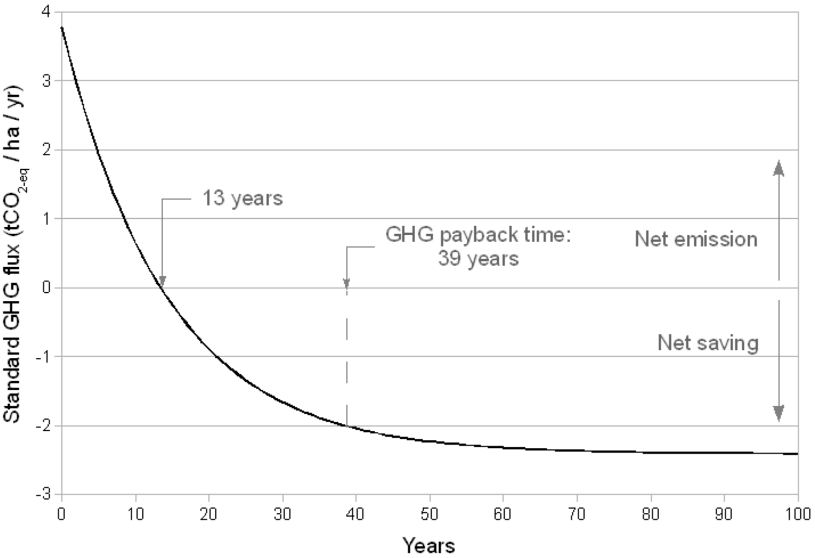

Figure 3: GHG impact dynamics of the first case study, standard GWP

GHG impact dynamics from figure 3 can be integrated in classical LCA results in two different ways [7-9]. The first one is to keep as the final LCA result the annual saving of the considered system, i.e. 33.2 gCO_{2-eq} / MJ in this case, and to complete it with an additional value: the GHG payback time, defined as the ratio of the soil carbon loss by the annual saving, i.e. 39 years in this case. The second way is to share out the soil carbon loss over a given period of time and then to aggregate the result with the annual saving. The methodological difficulty comes from the choice of the period of time: 20 years may be chosen to stay in line with the classical convention in LCA, 50 years because the soil carbon loss occurs roughly in such a period, 100 years because the scenarios are considered over this period of time, etc. If 20 years is chosen, the final LCA result is a net emission of 32.3 gCO_{2-eq} / MJ produced, so that ethanol impact is higher than gasoline impact; if 50 or 100 years are chosen, the final LCA result is a net saving of, respectively, 7.0 or 20.1 gCO_{2-eq} / MJ produced. Thus this choice is at the root of high discrepancies in LCA results.

The proposition of this work is to deal with such an issue by means of a temporal weighting using dynamic GWP. Figure 4 so describes the weighted GHG flux from the first case study.

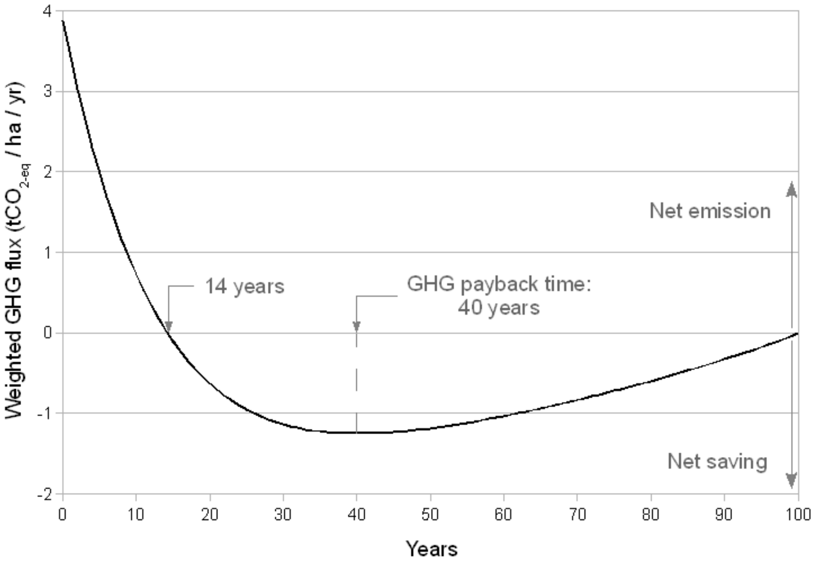

Figure 4: Weighted GHG impact of the first case study, dynamic GWP

Thus the total weighted GHG impact shows a similar GHG payback time as the standard impact and a saving of 45.5 tCO_{2-eq} / ha over 100 years, i.e. a saving of 6.5 gCO_{2-eq} / MJ produced. These results are similar to the 50 years sharing out assumption ones but this depends on the considered case study.

Finally application of dynamic GWP to this case study shows valid and able to prevent to state an additional subjective assumption concerning a period of time for sharing out. Indeed the assumptions required for the GWP calculations from the IPCC are enough to define dynamic GWP and so to weight GHG impact dynamics in order to get a single value. Furthermore GHG payback time and sharing out methods are only valid for a simple and single dynamic phenomenon whereas dynamic GWP can easily handle more complex scenarios integrating for instance in this case study a scenario of gasoline production impact related to oil scarcity, a biofuel production learning curve, etc.

Case study 2: Carbon sequestration credit of wood-based materials

Biomass-based materials and in particular wood-based materials might be a way to mitigate GHG emissions from the buildings sector. The two contradictory phenomena for the interest of wood as a building material compared to brick or concrete are generally lower GHG emissions due to the production phase and poorer thermal characteristics [10]. However carbon sequestration effect of wood is generally badly considered whereas storing CO_2 from the atmosphere during decades in furniture or buildings may be considered as an interesting carbon sink.

The objective of this second case study is to define a carbon sequestration credit for wood-based materials. In order to be able to complete an existing Life Cycle Inventory (LCI) database with the resulting values, no assumption will be made about the material production and disposal; though it is assumed that at the end of the material lifespan the embodied CO_2 is released to the atmosphere.

The considered scenario is thus that the wood-based material absorb a given amount of CO_2 due to photosynthesis at the production year, and release the same amount at the end of its lifespan. Carbon sequestration credit is then defined as the subtraction of CO_2 amount absorbed at year 0 and this same amount released at the end of its lifespan weighted by the corresponding dynamic GWP. Table 2 shows the resulting credits depending on the lifespan for cellulose, assumed to represent an absorption of 1.85 kgCO2 / kg [10], and for a GWP time horizon of 100 years.

Table 2: Carbon sequestration credit of cellulose-based material, using dynamic GWP for a time horizon of 100 years

Material lifespan (years)	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100 and more*
Carbon sequestration credit ($kgCO_{2-eq}$ / kg)	0.14	0.29	0.44	0.60	0.76	0.93	1.12	1.32	1.56	1.85

For comparison purposes, material impacts from 9 LCA-based tools for buildings range from -1.80 to 0.15 $kgCO_{2-eq}$ / kg for wood, 0.22 to 0.32 $kgCO_{2-eq}$ / kg for brick and 0.08 to 0.13 $kgCO_{2-eq}$ / kg for concrete [10]. Then credit values of cellulose-based materials from table 2 are not negligible compared to impacts of other common materials. Carbon sequestration effect is thus a key phenomenon to consider when dealing with biomass-based materials.

Conclusion and perspectives

As a part of the photosynthesis-respiration CO_2 cycle, biomass has quickly been seen as a solution to address climate change issues. However biomass uses imply some slow or delayed GHG emissions or uptakes which are important to take into account to assess sustainability. For LCA practice considering an GHG dynamics rather than punctual fluxes means weighting differently GHG fluxes over time. As any weighting methods different approaches can be used to define the weighting factors. The proposition of the present work is to stay in line with the existing conventions required to define GWP.

The resulting dynamic GWP, i.e. varying according to the GHG emission year, were so computed for a time horizon of 100 years and applied to two case studies: the integration of the carbon dynamics due to a land-use change into a biofuel LCA, and the definition of a carbon sequestration credit for biomass-based materials. In both cases dynamic GWP application was relevant and allowed to handle efficiently the dynamics issue.

However whereas the second case study defined credits directly usable to integrate the carbon sequestration effect of biomass into existing LCI databases, the first one only shows the applicability and interest of dynamic GWP for assessment of dynamic scenarios. But in the same way as an inaccurate system definition leads to wrong LCA results, dynamic GWP are a tool and will not help if the assessed scenarios are irrelevant. Dynamic GWP should thus be used for consequential LCA aiming at comparing scenarios and integrated in a prospective work.

Furthermore dynamic GWP calculations have been simplified in this work by assuming no connection of radiative efficiencies and abundance functions shape with the emission year. This is an approximation since these two factors depend on the atmosphere composition. Taking into account the GHG emissions scenarios from the IPCC [11] and using climate modelling could therefore improve dynamic GWP values relevance and accuracy.

Finally dynamic GWP only concern climate change and so account for one step towards dynamic LCA. Temporal weighting principles should thus be applied to the other impact categories in order to set up a complete and consistent dynamic LCA methodology.

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