IEooc_Methods4_Exercise11:

Considering time in life cycle inventories: dynamic characterization factors for greenhouse gases

Goal: *Get familiar with the global warming potential of greenhouse gases and the computation of global warming impacts of emissions from a system at different times. ('dynamic GHG accounting'). Apply dynamic GHG accounting to different test cases.*

Introduction and theory:

The global warming potential $GWP_i(T)$ is the most common metric to aggregated greenhouse gas emissions into a common warming impact indicator. It is defined as the ratio of the cumulative global warming impact of 1 kg of GHG *i* over the impact of 1 kg of CO_2 over the same time horizon *T*:

$$GWP_i(T) = \frac{a_i \cdot c_i \cdot \int_0^T R_i(t)dt}{a_{CO2} \cdot \int_0^T R_{CO2}(t)dt} \quad (1)$$

Where a_i is the specific (mass-based) radiative forcing of GHG *i* (see also exercise IEooc_Background2_Exercise2 on the GWP). c_i is an additional correction factor for indirect effects (see exercise IEooc_Background2_Exercise2). R_i is the so-called impulse response function of the atmosphere, i.e., the mass share of a pulse emission of GHG *i* at time *t=0* that is still present in the atmosphere after time *t* (see exercise IEooc_Background2_Exercise2, this variable is labelled C_i in Levasseur et al. (2010)).

$$[a_i] = W \cdot m^{-2} \cdot kg^{-1} \quad (2)$$

The instantaneous global warming potential was introduced by Levasseur et al. (2010) to introduce consistent time horizons into life cycle impact assessment (LCIA) and thus to allow for

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accounting for differences in global warming impacts of the product system for emissions that occur at different stages of the product life cycle.

Amongst others, this method enables us to compare the differences in GWP from wood energy use and material use from an attributional perspective.

The accompanying Excel workbook contains recent data on the coefficients and functions *a*, *c*, and *R(t)* for the three greenhouse gases CO_2, CH_4, and N_2O.

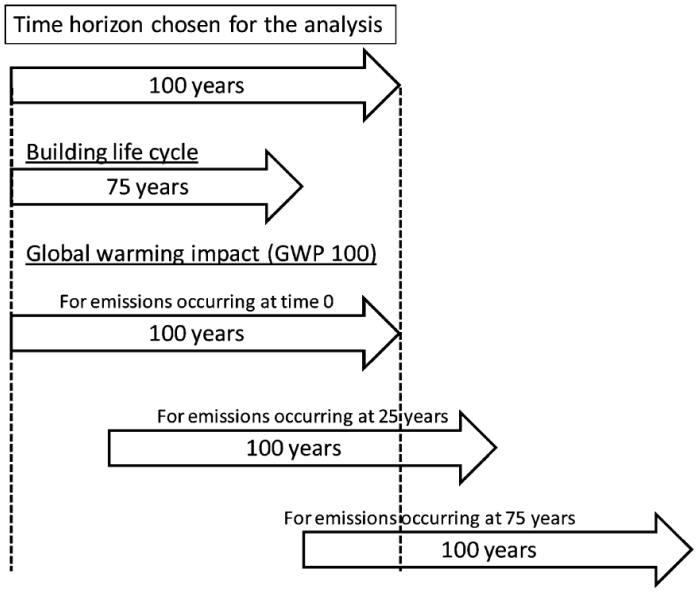

FIGURE 2. Illustration of the inconsistency in time frames for global warming LCIA with the example of a 75-year lifetime building.

Figure 1: From Levasseur et al. (2010): Illustration of the inconsistency in time frames for global warming LCIA with the example of a 75-year lifetime building. To establish consistency, the time horizon for each GHG pulse emissions in a given year is set so that the impact on global warming is accounted for only until the time horizon of the entire analysis. For example, if a maintenance-related emissions occurs at year 60, it contributes to the total GWP only with a time horizon of 100 – 60 = 40 years.

The instantaneous global warming potential is given by the integral over the continuous decay curve of the gas over one year, to convert from continuous time to a discrete time interval:

$$DCF_i(t)_{\text{instantaneous}} = \int_{t-1}^{t} a_i \cdot R_i(\tau) d\tau \quad (1)$$

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Now, we take a life cycle inventory $g_i(t)$ of greenhouse gases emitted from a product system of a given product or service. This inventory is represented by a list of different emissions of GHG *i* at time *t*, see Excel workbook for an example in columns E, F, and G of the main sheet.

For one given year *t* within the time horizon, the following convolution follows for the global warming impact of this year (Levasseur et al. (2010)):

$$GWI(t) = \sum_i \sum_{j=0}^{t} g_i(j) \cdot DCF_i(t-j)_{\text{instantaneous}} \quad (2)$$

By summing up over all annual impacts until the time horizon T, the cumulative GWI follows:

$$GWI_{CUM}(T) = \sum_{t=0}^{T} GWI(t) = \sum_{t=0}^{T} \sum_i \sum_{j=0}^{t} g_i(j) \cdot DCF_i(t-j)_{\text{instantaneous}} \quad (3)$$

And, by normalizing against a pulse emission of 1 kg CO_2 over the same time horizon:

$$GWP_{dyn}(T) = \frac{GWI_{CUM}(T)}{a_{CO_2} \cdot \int_0^T R_{CO_2}(\tau) d\tau} \quad (4)$$

The equation for GWI_{Cum} contains three sums (one over all years *t* where an impact occurs, one over all years *j* where an emissions occurs, and one over all GHG *i*) and one integral (to integrate over the continuous function $R_i(t)$ for one year in the equation for $DCF_{instantaneous}$).

If we are only interested in the total GWP at time horizon T and not the single-year contributions *GWI(t)*, we can simplify the above expression as follows:

First, we change the summation indices according to Fig. 2. The green line (not all are shown for clarity) illustrate the two sums, first over t (each t defining a new vertical line) and then, for each green line, from 0 to t. Alternatively, one can sum up first over j (from 0 to T) and then, for each fixed j, from t = j to t = T (blue lines). Thus, we find that, for any function *X(t,j)*:

$$\sum_{t=0}^{T} \sum_{j=0}^{t} X(t,j) = \sum_{j=0}^{T} \sum_{t=j}^{T} X(t,j) \quad (5)$$

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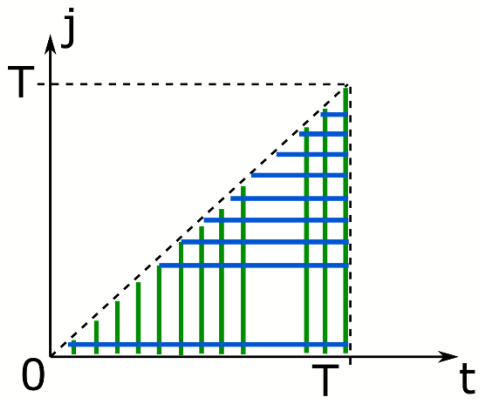

Figure 2: Two different ways to sum up the triangle underneath the *j = t* line. See text for details.

We now apply this change in the summation order to the equation for $GWI_{Cum}(t)$:

$$GWI_{CUM}(T) = \sum_{j=0}^{T} \sum_{i} \sum_{t=j}^{T} g_i(j) \cdot DCF_i(t-j)_{\text{instantaneous}} \quad (6)$$

Now, we reorder the sums, using that *g* depends on *j* and not on *t*:

$$GWI_{CUM}(T) = \sum_{j=0}^{T} \sum_{i} g_i(j) \cdot \sum_{t=j}^{T} DCF_i(t-j)_{\text{instantaneous}} \quad (7)$$

Now, we see that the sum of the multiple instantaneous DCFs can be added together as follows:

$$\sum_{t=j}^{T} DCF_i(t-j)_{\text{instantaneous}} = DCF_i(0) + DCF_i(1) + DCF_i(2) + \ldots + DCF_i(T-j)$$

$$= \int_{-1}^{0} R_i(\tau)d\tau + \int_{0}^{1} R_i(\tau)d\tau + \int_{1}^{2} R_i(\tau)d\tau + \ldots + \int_{T-j-1}^{T-j} R_i(\tau)d\tau$$

$$= 0 + \int_{0}^{T-j} R_i(\tau)d\tau$$

(8)

In the equation above, the index 'instantaneous' was dropped from the terms on the right sight to increase readability (first row, right side). Then (second row), we replace DCF by its definition, and we see (third row), that all contributions add up, which makes sense, since the

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cumulative global warming impact of an emission at time *j* until time horizon *T* is proportional to $\int_0^{T-j} R_i(\tau)d\tau$. Here, we also used the that impulse response function *R(t)* is zero for any negative times (times before the emission), and hence, the first term in the third line of the last equation, $DCF(0)_{instantaneous}$, is 0.

In a last step, we insert the above result into the equation for $GWI_{Cum}(t)$, rename the summation index *j* into *t* (which is not needed anymore in the above equation), and summarize. Because for any emission at year t before the time horizon T, all global warming impact between t and T is accumulated and calculated as $\int_0^{T-t} R_i(\tau)d\tau$, the calculation above can be simplified into:

$$GWI_{CUM}(T) = \sum_{t=0}^{T} GWI(t) = \sum_{t=0}^{T}\sum_{i} g_i(t)\cdot a_i \cdot \int_0^{T-t} R_i(\tau)d\tau \quad (9)$$

This equation requires the computation of the integral over the impulse response function $R_i(t)$ for different time horizons, for which an analytical solution exists for all GHG. Summing up over the different GHG *i* in the inventory and over the contributions of the different years *t* is easily done, also in Excel or other spreadsheet tools.

Carbon emitted to the atmosphere will not stay there forever, but will be distributed between atmosphere, oceans, and biosphere in the subsequent years. The decay of atmospheric CO_2 following a pulse emission at t=0, $R_{CO2}(t)$, is given by the so-called Bern carbon cycle-climate model using a background CO_2 concentration of 378 ppm (equation 1), (Levasseur et al., 2010):

$$R_{CO2}(t) = a_0 + a_1 \cdot \exp(-t/T_1) + a_2 \cdot \exp(-t/T_2) + a_3 \cdot \exp(-t/T_3) \quad (10)$$

With $a_0 = 0.217$, $a_1 = 0.259$, $a_2 = 0.338$, $a_3 = 0.186$, $\tau_1 = 172.9$ yr, $\tau_2 = 18.51$ yr, and $\tau_3 = 1.186$ yr.

This equation applies to all CO_2 flows to the atmosphere, fossil and biogenic. It is also used to model the effect of removing CO_2 from the atmosphere, e.g., via biomass growth (photosynthesis).

For details regarding GWP calculations, including specific radiative forcing and the correction factors applied, please check IEooc_Background2_Exercise2 on the global warming potential (GWP).

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dynLCA workbook:

The Excel workbook *IEooc_Methods4_Exercise11_dynLCA_Workbook.xlsx* for this exercise contains an implementation for $GWP_{dyn}(T)$ for any GHG inventory for CO_2, CH_4, and N_2O and a time horizon of 100, 200, and 500 years (sheet 'DynLCA_Convolution').

System definition:

This exercise introduces the accounting of carbon emissions and sequestration that are distributed over the life cycle of a product. For example, when a forest gradually sequesters CO_2 after a logging impact or when woody biomass is stored in form of a construction material before being burned for energy recovery. The life cycle of the forest product starts with the moment it is harvested from the forest (process 1) and then either used as material (modelled as carbon flow $F_{12}(t=0)$ to process 2) or used as energy carrier (modelled as carbon flow $F_{13}(0)$ to process 3) (Fig. 3). After a certain use time T, the wood used as material is discarded (modelled as carbon flow $F_{23}(0)$ to process 3). All inflows to process 3 (energy recovery) are emitted back to the atmosphere (wood burning) within the same accounting period.

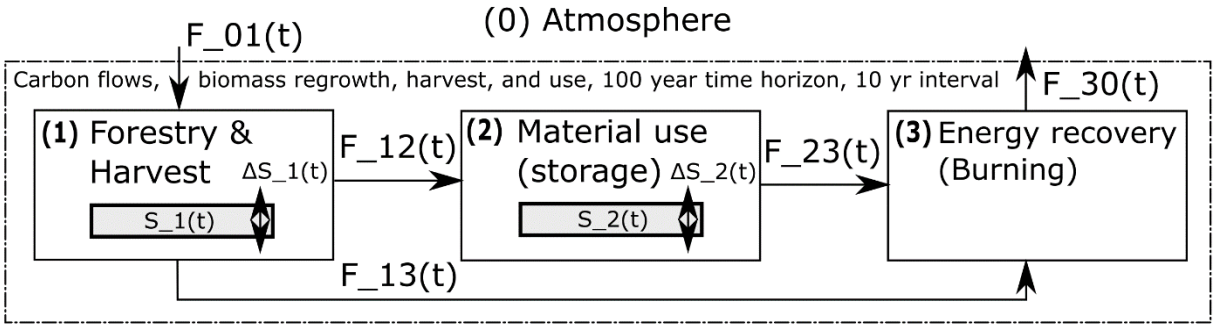

Figure 3: System definition for the life cycle of a wood-based product with either immediate use as energy carrier or use as material, followed by energy recovery. To keep calculations simple, the system is modelled in time steps of 10 years. The large boxes represent the three processes, the light grey boxes in the processes symbolize the carbon stocks in the processes, and the arrows on top of the grey boxes the carbon stock changes.

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Questions and tasks:

With the Excel tool (or any other custom implementation of GWP_{dyn}) and the system definition in Figure 3 above, the following problems shall be addressed:

Task 1: Consider a pulse emission of 1 kg of CO_2 at different years: t = 0, t = 50 years, t = 100 years. Calculate the resulting GWP for the time horizons of 100, 200 and 500 years as given in the Excel workbook, and interpret your results!

Task 2: Compare the GWP for different forest management scenarios and different storage periods for wood products.

Consider the following two stylized forest management scenarios:

FM1: climate-neutral forestry: At the landscape level, there shall be a constant regrowth of trees so that harvest losses are compensated through regrowth and the forest carbon pool stays constant over all forest enterprises in a region. A certain amount of wood can be logged each year, which is available as energy source and construction material.

FM2: clear-cutting forests with subsequent land-sealing, e.g., for settlements. Here, for each harvested/clear-cut ton of carbon in timber, about another half ton of carbon in leaves, branches, roots, and soil decomposes.

For the harvested wood, we have two use scenarios:

WU1: Use as energy carrier after harvest

WU2: Use as structural timber with a lifetime of 100 years, subsequent use as energy carrier.

a) Quantify, for all four possible forest management and use scenario combinations, the relevant carbon flow time series in the system definition in Figure 3!
b) From these flows, compile the GHG inventory g(t) for each of the four scenario combinations!
c) Calculate the dyn GWP of the four inventories for the time horizons of 100, 200, and 500 years and compile these results in a table!
d) Interpret and discuss your results!

As reference quantity, use a carbon mass m = 0,273 tons that corresponds to CO_2 emissions of 1 ton!

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Task 3: Estimate the impact of carbon storage on the embodied GHG emissions for buildings

From a comparative study on concrete and wooden buildings (Krebs and Pauliuk 2022, https://doi.org/10.6094/UNIFR/225544) we roughly know the material composition of concrete-based and wood-based multi-family houses for the temperate climate zone in Europe. The concrete-based building requires a total of about 1220 kg of concrete per m² (here, screed and bricks were aggregated and assumed to be made from concrete or similar materials). For the wooden building, it is ca. 540 kg concrete (mostly for basement and ceilings) and ca. 190 kg wood per m² (Tables 3 and 4 in Krebs and Pauliuk 2022). The global warming impact (GWP100) of concrete is ca. 0.11 kg CO_2-eq per kg (from ecoinvent, see data details in sample solution). The carbon content of construction wood is ca. 50 mass-%.

a) How large is the concrete-related GWP100 for a 120m² family apartment in such buildings?
b) How large is the attributional GWP of the wood use, with a 100 year storage period as construction wood, calculated with dynLCA? Repeat the calculation for a 100, 200, and 500 year time horizon. Interpret your findings!

Task 4: The single stem perspective with dynLCA

Consider the plot of land where a single tree grows, and two different scenarios. The trees in this forest all have a lifetime from 100 years, from seed to felling.

In the first scenario S1, the plot is empty at t = 0 and the tree starts growing. We model the tree growth simply by an uptake of 1 unit of atmospheric carbon at t = 50 years. After 100 years, the tree is felled and used as energy source (re-emission of 1 unit of carbon to the atmosphere).

In the second scenario S2, the plot is occupied with a fully grown tree that is harvested at t = 0 (emission of 1 unit of carbon to the atmosphere) and then, a new tree grows and its growth again is modeled simply by an uptake of 1 unit of atmospheric carbon at t = 50 years. This system boundary corresponds to the one used by Guest, Cherubini, and Stromman (2013).

Scenario S3 is the reference case, where we look at the landscape level: In an ideal climate-neutral managed forest, the carbon stock in wooden biomass is constant and each harvest is compensated for by a sequestration from tree growth on other plots of land. Hence, we have a harvest flow and a sequestration flow at t = 0, both of the same size.

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Tasks:

a) Quantify the carbon flows F_01(t) and F_30(t) in the system definition in Figure 3 for all three scenarios!
b) Calculate GWPdyn with a time horizon of 100 years for the three scenarios!
c) Interpret your findings!

Literature and references:

IEooc_Background2_Exercise2 on the global warming potential (GWP), see http://www.teaching.industrialecology.uni-freiburg.de/

IEooc_Application4_Exercise6 on the concept of payback time in life cycle thinking and on how to take into account the timing of emissions and sequestration of carbon in the calculation of the global warming potential (GWP), see http://www.teaching.industrialecology.uni-freiburg.de/

Guest, G., Cherubini, F. & Strømman, A. H. Global Warming Potential of Carbon Dioxide Emissions from Biomass Stored in the Anthroposphere and Used for Bioenergy at End of Life. J. Ind. Ecol. 17, 20–30 (2013).

Leonid Krebs und Stefan Pauliuk (2022). Szenarioanalyse für Materialverbrauch, Energiebedarf und Klimaauswirkungen des geplanten Stadtteils „Dietenbach“ in Freiburg. Industrial Ecology Freiburg (IEF) Working Paper 2(2022), Universität Freiburg im Breisgau. DOI 10.6094/UNIFR/225544

Levasseur, A., P. Lesage, M. Margni, L. Deschenes, and R. Samson. 2010. Considering Time in LCA : Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environmental Science & Technology* 44(8): 3169–3174.

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