GWP factors and warming payback times as climate indicators of forest biomass use cycles

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Objectives of the study

- The issue: Climate impact of transient emissions and sustainable long-rotation forestry and wood use
- Wood use C neutral over rotation, but temporary C debt in proportion to no-use baseline
- On the other hand: climate benefits in case wood use has an impact on fossil C emissions
- Method: GWP factors both for biomass resource \( (GWP_{bio}) \) and displacement of fossil C emissions \( (GWP_{biouse}) \), Warming Payback Time
Calculation method

Basic assumption: cumulative radiative forcing (absolute global warming potential) appropriate measure for the climate impacts within some prescribed timeframe
Generalisation of the GWP$_{\text{bio}}$ factors to displaced emissions

- Cherubini et al. (2011): C debt due to biomass harvest, GWP$_{\text{bio}}$ factor introduced, analogous to the GWP factors defined for non-CO$_2$ GHGs, whose atmospheric dynamics different


- **Present study:** Extension of the GWP$_{\text{bio}}$ factors. Climate impacts of displacement of fossil fuels and fossil C intensive products by biomass; also consideration of other than instant pulses


Basis of the radiative forcing calculations (1): 
GWP factors and AGWP (cumulative radiative forcing)

Cumulative radiative forcing of fossil C pulse emission (irreversible, no flow back to tectonic C stocks):

\[
AGWP_{fos}(T) = \int_{0}^{T} RF \left( S_{fos}(t) \right) dt
\]  

(1)

where \( RF \) is the instant radiative forcing, and \( S \) the additional atmospheric concentration due to the emission; concentration dynamics calculated by the impulse response model by IPCC.

Cumulative radiative forcing of biogenic C pulse emission due to harvest (reversible, sequestered back to biomass on the same area of land, if forestry on sustainable basis):

\[
AGWP_{bio}(T) = \int_{0}^{T} RF \left( S_{bio}(t) \right) dt
\]  

(2)

Note: also other climatic forcers than GHGs (e.g. surface albedo) could be included in AGWP.
Basis of the radiative forcing calculations (2): GWP factors and AGWPs (cumulative radiative forcing)

Similar integral can be presented for the climate benefits of the harvested biomass use cycle with respect to its fossil alternatives:

$$AGWP_{biouse}(T) = \int_{0}^{T} \left( RF \left( S_{displ}(t) \right) + RF \left( S_{seq}(t) \right) \right) dt$$  \hspace{1cm} (3)

where $S_{displ}$ and $S_{seq}$ are the atmospheric concentration changes due to displaced fossil C emissions and to biogenic C sequestered into wood products, respectively.
Basis of the radiative forcing calculations (3): GWP factors and AGWPs (cumulative radiative forcing)

Relative climate impact of the biogenic C pulse emission (incl regrowth) in proportion an equal fossil C pulse emission (no flow back to tectonic stocks) (Cherubini et al. 2011):

\[
GWP_{bio}(T) = \frac{AGWP_{bio}(T)}{AGWP_{fos}(T)}
\]  

\(GWP_{bio}\) factor a dimensionless index, a function of the mitigation timeframe \(T\).

Analogous to definition of GWP factors of non-CO\(_2\) GHGs describing their CRF in proportion to CO\(_2\); \(T = 100\) years commonly used.
Basis of the radiative forcing calculations (4): GWP factors and AGWP\(_s\) (cumulative radiative forcing)

The GWP index can be generalised to the whole biomass lifecycle, and also to the case where displaced fossil fuel emissions are considered:

\[
GWP_{\text{netbio}}(T) = \frac{AGWP_{\text{bio}}(T) + AGWP_{\text{biouse}}(T)}{AGWP_{\text{fos}}(T)} \tag{5}
\]

\[
= GWP_{\text{bio}}(T) + GWP_{\text{biouse}}(T) \tag{6}
\]

Where \(GWP_{\text{netbio}}\) is the GWP of the net climate impact of the biomass harvest and utilisation, and \(GWP_{\text{biouse}}\) that of the plain use cycle.
Basis of the radiative forcing calculations (5): GWP factors and AGWPs (cumulative radiative forcing)

Note that in case biomass is used just to bioenergy displacing fossil fuels (no temporary product C stock):

\[ GWP_{biouse}(T) = -DF \]  \hspace{1cm} (7)

where DF is the displacement factor (Schlamadinger and Marland, 1996 and 1997).
Results: Case 1

Bioenergy from forest harvest residues
Case: harvest residues to bioenergy; assumptions:

- Decay of harvest residues or Norway spruce in climate conditions of Southern Finland; from the study of Repo et al. (2010)*.
- Dynamic C debt: Use of residues to bioenergy causes an immediate emission and C debt with respect to no-use baseline where residues decay slowly on site.
- Decay depends on residue diameter. Branches (1 cm, 2 cm, 5 cm) and stumps (10 cm, 20 cm, 26 cm and 35 cm) considered.

Example 1:
- Emission from pulse use (1 MgC) of 5 cm branches vs fossil C pulse at 2010
- GWP factors and cumulative C balance of biomass debt and displaced emissions
- Displacement factor DF = 0.6
Example 2:

- Emission from **step use** (1 MgC/yr) of branches and stumps vs fossil C step at 2010

- stepGWP factors (generalisation of the GWP concept) and cumulative C balance of biomass debt and displaced emissions of bioenergy from 5 cm branches

- Displacement factor DF = 0.6
- Warming payback time as a function of DF for **pulse use** of branch and stump harvest residues

- Warming payback time as a function of DF for **step use** of branch and stump harvest residues
$GWP_{bio}(100\text{ yrs})$ of C debt due to harvest residues as a function residue diameter
Case 2

Material substitution by wood products
Case: stemwood to long-lived wood products + bioenergy; assumptions:

- GHG emissions of construction a wood office building compared with a conventional concrete one; LCA data from Häkkinen and Wirtanen (2006)*.
- Raw material: stemwood of Scots pine; 40% sequestered to wood pr; by-products used to the renewable energy portion of processing of wood products, excess to displace fossil fuels elsewhere.
- Stemwood growth curve based on representative sample from Finland (MOTTI simulator, Hynynen et al. in Metla)

Estimated average development of stemwood biomass (Scots pine, Southern Finland) as a function of stand age. Statistics not representative beyond 140 years (few samples, uncertainties concerning natural disturbances).
Example:

- Emission from **pulse use** of 763 MgC of stemwood (=demand for wood building) vs. fossil C pulse at 2010
- Final felling at stand age 80 years
- GWP factors and cumulative C balance of biomass debt and displaced emissions
- Displacement factor DF = 0.6
- Service life of building = 50 years (=underestimate); demolition wood to bioenergy
$GWP_{bio}$ factors of stemwood (Scots pine) as a function of stand age at final felling (dotted lines denote high uncertainty).
Discussion and conclusions (1)

- Two dimensionless GWP indicators, one for the biomass resource, the other for the relative impact of the biomass use cycle.
- Similar index could be developed for the "absolute" impact of the use cycle. When mitigation timeframe is fixed GWP could provide a kind of physical discounting factor for LCA by which the impact of future lifecycle emissions of the biomass use cycle could be transformed to a carbon footprint, or an equivalent fossil C (or CO\textsubscript{2}) emission taking place at present.
- In the short term the use of "slow" boreal forest biomass appears just to increase the warming impact especially when the efficiency of biomass use is low.
- The true displacement factor DF obviously lower than the theoretical one due to the dynamics of the energy markets. DF a useful parameter that should be varied in the analysis.
Discussion and conclusions (2)

 The displacement efficiency may even decrease in the future, along with a lowering C intensity of the future energy system (from this point even landfilling of biomass to be considered!).

 The sink or sequestration option is favourable in the short, but the risk of natural disturbances should be considered; stochastic analysis required.

 The forest sink is not a sustainable option in the meaning that it cannot be continued forever due to saturation. Risks of losing the biomass due to disturbances and production capacity of the forest.

 On the other hand: negative(!) emissions required in the second half of the secondary half of the century to avoid critical global warming, C sinks needed.

 Climate change mitigation is management of a transient; temporary means like C sinks must be an option among others.
Supplementary material:
Basis of the radiative forcing calculations (1)

The decay of the CO$_2$ pulse in the atmosphere with time $t$ is given* by

$$a_0 + \sum_{i=1}^{3} a_i \cdot e^{-t/\tau_i}$$

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

*The CO$_2$ response function is estimated based on the revised version of the Bern Carbon cycle model (Bern2.5CC;Joos et al. 2001) using a background CO$_2$ concentration value of 378 ppm. This approximation is used in IPCC Fourth Assessment Report (AR4), Climate Change 2007: The Physical Science Basis, p. 213.
Supplementary material: 
Basis of the radiative forcing calculations (2)

In the calculations a “compartment model” having the above pulse response was used:

\[ C_{\text{emission}} \]

\[ \begin{align*}
S_0 & \quad 0.217 \\
S_1 & \quad 0.259 \\
S_2 & \quad 0.338 \\
S_3 & \quad 0.186
\end{align*} \]

\[ \tau_1 = 172.9 \text{ yrs} \]

\[ \tau_2 = 18.51 \text{ yrs} \]

\[ \tau_3 = 1.186 \text{ yrs} \]

First-order decay, time constants \( \tau_1, \tau_2 \) and \( \tau_3 \)

Additional concentration in the atmosphere \( S = S_0 + S_1 + S_2 + S_3 \)
Supplementary material: 
Basis of the radiative forcing calculations (3)

The background GHG concentration $\text{CO}_2(t)$ in was assumed to develop so that the $2^\circ\text{C}$ stabilisation target 450 ppm$_{eq}$ will be met by 2100.

\[
\text{RF}(\text{CO}_2) = 5.35 \text{ W m}^{-2} \left( \ln \frac{\text{CO}_2(t)}{\text{CO}_2(t_0)} \right)
\]

In the study the additive RF due to the emissions was considered.