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Introduction

It has been recommended (Fearnside et al., 2000) that carbon storage and delayed emissions of greenhouse gases (GHGs) should be treated in Impact Assessment by excluding impacts outside the 100-year assessment period. This approach is open to criticism but is at least consistent with the approach used more widely, for example in the Kyoto protocol. This note sets out an analytical method to implement this approach using the Lashof method (see Fearnside et al., 2000). The full mathematical functions are developed, with simplified expressions which can be used, within limits, for a single GHG release and for steady continued release over a period of some years. Elements of this analysis have been incorporated into the BSI/Carbon Trust PAS 2050 specification for carbon labelling.

Basic Formulation

Figure 1 shows the basic approach to accounting for delayed release (originally proposed by Nebel *et al*, 2003). A single emission at time zero leads to an increase in radiative forcing which decays over time, proportional to its concentration in the atmosphere. The decay function is denoted by *f(t)*. Over the accounting period of T years (conventionally T=100), the corresponding Greenhouse Warming Potential (GWP) is

$$I_T = \int_o^T f(t)dt \qquad \text{(A)}$$

If the emission is delayed by t_o years, the GWP reduction within the accounting period is given by the shaded area in Figure 1:

$$I(t_0) = \int_{T-t_0}^{T} f(t)dt \qquad \text{(B)}$$

The fractional saving is $I(t_0)/I_T$.

The approach proposed here avoids uses the expression for *f(t)* developed by the Intergovernmental Panel on Climate Change (IPCC) for carbon dioxide. The form of *f(t)* is different for other GHGs, some decaying faster and some more slowly than carbon dioxide. If *f(t)* is available for another GHG, then the analytical forms given here can be used. As a default, it is suggested that the expressions for carbon dioxide be used for mixtures of GHGs.

Evaluation of GWP Reduction

IPCC (2007) gives the decay function for carbon dioxide as

$$f(t) = a_0 + \sum_{i=1}^{3} a_i.\exp(-t/\tau_1) \qquad \text{(C)}$$

Table 1 gives the IPCC values for the parameters in eqn. (C). For *T* = 100 years, *f(T)* = 0.364; i.e. of carbon dioxide emitted at time zero, 36.4% is estimated to remain in the atmosphere after 100 years. The corresponding value for GWP is, from equation (A),

$$I_T = \int_O^T \left[a_o + \sum_{i=1}^{3} a_i.\exp(-t/\tau_i) \right] dt$$
$$= a_o T + \sum_{i=1}^{3} a_i \tau_i \left[1 - \exp(-T/\tau_i) \right] \qquad \text{(D)}$$

For T = 100 years, I_T = 47.8.

From equations (B) and (C), the GWP reduction if an emission is delayed by t_o years is

$$I(t_0) = a_0 t_0 + \sum_{i=1}^{3} a_i \tau_i \left[\exp\left(\frac{t_o - T}{\tau_i} \right) - \exp\left(\frac{-T}{\tau_i} \right) \right] \qquad \text{(E)}$$

It would be simple to provide a table of values of $I(t_o)/I_T$.

It is also possible to extend the analysis for other cases. Steady release over t_1 years is treated here as an example. The fractional saving relative to instantaneous emission at the beginning of the accounting period; i.e. for continuous emission from t=0 to t=t_1, is given by:

$$J(t_1) = \left(\int_0^{t_1} I(t_0) dt_0 \right) / I_T \qquad \text{(F)}$$

Again, it would be straightforward to provide a table of values for $J(t_1)$

Approximations for Short Delay Times

A simplification to equations (D) and (F) has also been developed. The principle is shown in Figure 1. Rather than using the analytical curve HF (i.e. *f (t)*), the decay function over this interval can be approximated by the tangent to the decay curve at point F, i.e. H'F in Figure 1. The (negative) gradient of the tangent is

$$f'(T) = \left(\frac{df}{dt}\right)_{T=0}$$

$$= \sum_{i=1}^{3} \frac{-a_i}{\tau_i} \exp(-T/\tau_1) \qquad \text{(G)}$$

If the accounting period is 100 years, $f'(100) = -9.2 \times 10^{-4}$ year^{-1}; a very slow continuing decay, less than 0.1% of the initial concentration per year.

The approximate expression for *f(t)* is then

$$f(t) = f_T - f'(T)(T-t) \qquad \text{(H)}$$

The resulting expressions for GWP saving due to delayed emission are, from equations (B) and (F):

$$I(t_0) = \int_{T-t_0}^{T} [f_T - f'(T)(T-t)]dt$$

$$= t_0[f_T - f'(T)t_0/2] \qquad \text{(I)}$$

$$J(t_1) = \frac{1}{I_T}\int_0^{t_1} [f_T t_0 - f'(T)t_0^2/2]dt_0$$

$$= (t_1^2/2I_T)[f_T - f'(T)t_1/3] \qquad \text{(J)}$$

Inserting the values for T=100 gives

$$I(t_0) = 0.364t_0 + 4.6\times10^{-4}t_0^2 \approx 0.364t_0 \qquad \text{(K)}$$

i.e. $I(t_0)/I_T = 0.0076t_0 + 9.6\times10^{-6}t_0^2 \approx 0.0076t_0$ (L)

$$J(t_1) = t_1^2[3.8\times10^{-3} + 3.2\times10^{-6}t_1] \approx 3.8\times10^{-3}t_1^2 \qquad \text{(M)}$$

These expressions slightly underestimate the GWP saving, but the inaccuracy is small for delay times up to 25 years.

Reference

Fearnside, P.M., Lashof, D.A. and Moura-Costa, P., 2000, "Accounting for time in mitigating global warming through land-use change and forestry", *Mitigation and Adaptation Strategies for Global Change* **5**: 239-270.

Symbols

a_0, a_1, a_2, a_3	Parameters in IPCC expression for decay of carbon dioxide in atmosphere
$f(t)$	Fraction of GHG remaining in the atmosphere t years after emission.
f_T	Fraction remaining after accounting period (T years).
$f'(t)$	Rate of decay of GHG concentration at time t years after emission (year^{-1}).
I_T	GWP resulting from presence of GHG in atmosphere over accounting period of T years.
$I(t_0)$	GWP saved within accounting period by delaying emission by t_0 years.
T	Length of time defining accounting period for GWP (years).
t	Elapsed time (years)
t_0	Delay in emission of GHG (years)
τ_1, τ_2, τ_3	Time constants in IPCC expression for decay of carbon dioxide in atmosphere.
$J(t_1)$	Fractional saving in GWP if GHG releases continue over a period of t_1 years.

Table 1 Parameters in IPCC decay function for carbon dioxide

Coefficients	**Time constants (years)**
$a_0 = 0.217$	
$a_1 = 0.259$	$\tau_1 = 172.9$
$a_2 = 0.338$	$\tau_2 = 18.51$
$a_3 = 0.186$	$\tau_3 = 1.186$

Figure 1 Delayed GHG release: real concentration decay

T - Accounting period (normally 100 years)

f_T - f(T); i.e. the fraction of initial RF remaining at the end of the accounting period

t_0 - Delay in GHG release