

Offsetting methane emissions – An alternative to emission equivalence metrics

A.R. Lauder^a, I.G. Enting^{b,*}, J.O. Carter^c, N. Clisby^b, A.L. Cowie^d, B.K. Henry^{e,**}, M.R. Raupach^f^a Carbon Grazing, 31 Bunratty Street, The Gap, Qld 4061, Australia^b MASCOs, 139 Barry Street, The University of Melbourne, Vic 3010, Australia^c Department of Science, Information Technology, Innovation and the Arts, GPO Box 2454, Brisbane, Qld 4001, Australia^d Rural Climate Solutions, University of New England/NSW Department of Primary Industries, Armidale, NSW 2351, Australia^e IFE, Queensland University of Technology, 2 George Street, Brisbane, Qld 4001, Australia^f CSIRO Marine and Atmospheric Research, Black Mountain, ACT 2601, Australia

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ABSTRACT

It is widely recognised that defining trade-offs between greenhouse gas emissions using 'emission equivalence' based on global warming potentials (GWPs) referenced to carbon dioxide produces anomalous results when applied to methane. The short atmospheric lifetime of methane, compared to the timescales of CO₂ uptake, leads to the greenhouse warming depending strongly on the temporal pattern of emission substitution.

We argue that a more appropriate way to consider the relationship between the warming effects of methane and carbon dioxide is to define a 'mixed metric' that compares ongoing methane emissions (or reductions) to one-off emissions (or reductions) of carbon dioxide. Quantifying this approach, we propose that a one-off sequestration of 1 t of carbon would offset an ongoing methane emission in the range 0.90–1.05 kg CH₄ per year. We present an example of how our approach would apply to rangeland cattle production, and consider the broader context of mitigation of climate change, noting the reverse trade-off would raise significant challenges in managing the risk of non-compliance.

Our analysis is consistent with other approaches to addressing the criticisms of GWP-based emission equivalence, but provides a simpler and more robust approach while still achieving close equivalence of climate mitigation outcomes ranging over decadal to multi-century timescales.

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1. Introduction

Methane is the second most important of the anthropogenic greenhouse gases, after carbon dioxide. Efforts to mitigate anthropogenic climate change need to be able to assess the relative effectiveness of measures addressing the different greenhouse gases. To this end, various metrics of climate influence have been devised (see Fuglestedt et al., 2003; Forster et al., 2007, and Appendix A). Most notable are instantaneous 'radiative forcing' which leads to 'concentration equivalence' and global warming potential (GWP) which leads to defining 'emission equivalence'. 'Concentration equivalence' gives an instantaneous metric, based on the actual amounts of the gases in the atmosphere. In contrast, 'emission equivalence' gives an integrated metric, taking into account the different amounts of time that gases remain in the atmosphere after emission (Solomon et al., 2007, Glossary). The

need for a relation between emissions comes from the policy framework of mitigation. In markets where alternative goods can be substituted, the relative prices reflect a balance between relative supply costs and relative demand. However markets for greenhouse gas mitigation are created by regulation and agreement, and so, as noted in Appendix A, there is a need to specify the relative 'demand' so that the mix of mitigation activities to 'supply' this demand can be chosen on the basis of the lowest cost.

The main complicating feature in considering trade-offs between methane and most other greenhouse gases is the short atmospheric lifetime, compared to the timescales that dominate the response of carbon dioxide. As we discuss below, this disparity in timescales can necessitate intertemporal trade-offs.

Analysis of methane entails addressing a number of complicating factors: a poorly known budget, the concept of an effective lifetime, and the poorly-understood plateau in methane concentrations over the period 1999–2006. The atmospheric budget of methane is subject to considerable uncertainties (Dlugokencky et al., 2011) with a recent re-evaluation by Prather et al. (2012). The atmospheric content, M_{CH_4} , is well-known from direct measurement. The loss rate is less well-determined. There is a small loss from oxidation by soils, but the main loss is through oxidation in

* Corresponding author. Tel.: +61 3 8344 1796.

** Corresponding author. Tel.: +61 409343388.

E-mail addresses: ian.g.enting@gmail.com (I.G. Enting), beverley.henry@qut.edu.au (B.K. Henry).

the free atmosphere by processes involving the OH radical. This rate is determined indirectly from loss rates of other species (where the sources are better known). Laboratory measurements of reaction rates are used to relate the atmospheric loss rates of different gases. Observations of methyl chloroform (CH_3CCl_3) have played the main role in such determinations of the methane loss rate. Once the loss rate is determined, the source is determined from the relation

$$\text{Growth rate} = \text{sources} - \text{loss rate} \quad (1.1)$$

This means that the total of sources is relatively tightly constrained (Dlugokencky et al. (2011) indicate $\pm 15\%$) while contributions from particular classes of source are much more poorly known, with some components uncertain by a factor of 2 (Dlugokencky et al., 2011). However methane emissions from enteric fermentation in ruminants are known to make an important contribution to both the natural methane budget and to the human perturbation that has led to a 150% increase in atmospheric methane concentrations since pre-industrial times. The role of methane from livestock has recently been reviewed by Lassey (2008). A minor issue is that for ruminant methane emissions, the carbon originally comes from atmospheric CO_2 through photosynthesis and so there is no extra radiative forcing when the CH_4 is oxidised to CO_2 . If methane is offset by terrestrial carbon sequestration rather than reductions of emissions of fossil carbon, then the issue of consequent changes in aerosol forcing (Wigley, 1991; Hansen et al., 2000) is largely absent.

Where the loss processes for a gas are unaffected by the gas itself, loss from a pulse follows an exponential decay whose timescale is the atmospheric turnover time. For CO_2 this is not the case, and the pulse response needs to be expressed in a more complicated manner – commonly as a sum of exponentials. As discussed by Prather (1994, 1996), methane is an intermediate case, where a single exponential gives a good representation of the pulse response, but the timescale, termed the ‘effective lifetime’, is longer than the bulk turnover time. This indirect effect of methane through changes in atmospheric hydroxyl (OH) is characterised by Eqs. (2.5)–(2.7).

The limitations of the concept of CO_2 -equivalent emissions defined by the 100-year GWP, as applied in the Kyoto Protocol, have been widely noted. The problems are particularly serious when considering stabilisation of atmospheric concentrations of greenhouse gases. For example Reilly et al. (1999) give an example (cases 2' and 3' in their Fig. 3a) where Kyoto-equivalent emission pathways give a 1990–2100 warming of 0.5°C for multi-gas reductions, but 1.2°C for ‘equivalent’ CO_2 -only reductions. Manning and Reisinger (2011) give a more recent example of a study that explores the limitations of emission-equivalence based on GWPs in the context of stabilisation.

A number of studies have explicitly considered the role of CH_4 in climate mitigation. The general conclusion (Brook and Russell, 2007, for example) is that CH_4 reductions can play a useful role in the context of large reductions (or at least stabilisation) of CO_2 emissions. A more detailed study (Kheshgi et al., 1999) notes that projections to 2100 give a 3 W m^{-2} radiative forcing from CO_2 even with stabilisation at 450 ppm (the WRE450 scenario from Wigley et al., 1996), while methane only contributes 1 W m^{-2} even under the modified business as usual (IS92a) scenario. These authors also note the possibility of reducing methane concentrations by reducing emissions of other gases (CO , NO_x) that reduce atmospheric OH levels. The ‘alternative scenario’ proposed by Hansen et al. (2000) attracted great attention by proposing that reductions in methane emissions were preferable to reductions in CO_2 emissions. In part this was because, as noted by Wigley (1991), many CO_2 emission activities also produce aerosols that cause cooling. It is however, important to note that while the ‘alternative scenario’ proposed delaying CO_2 emission reductions for several decades, it did assume no increase in CO_2 emissions above the level in the year 2000.

As a way of reducing the need for the inter-temporal trade-offs that are necessitated by the use of GWPs, we propose a ‘mixed metric’ in which methane offsets are based on comparing on-going methane emissions to one-off removals of CO_2 . This is because the concentration of methane (a short-lived gas) is determined by current and recent emissions, whereas the concentration of CO_2 is determined by prior emissions over a much longer time frame. In particular we propose a level of one-off carbon sequestration that will offset ongoing methane emissions when considered over several centuries, and more than compensate for ongoing methane emissions over the decadal scale if the pool accumulates rapidly. If the sequestered carbon pool is built up gradually, then a closer equivalence is achieved over the decadal and multi-decadal timescales. This modified form, with progressively increasing sequestration, can be regarded as an integrated form of an approximate solution of the inverse problem (Wigley, 1998) whose solution gives the time-varying release of methane that has, at all times, equivalent radiative forcing to a pulse release of carbon dioxide. This was expressed in terms of a ‘forcing equivalent index’ (FEI). Manning and Reisinger (2011), discussed in more detail below, have shown an example of a particular case of such CO_2 : CH_4 equivalence in the specific calculation of stabilisation of radiative forcing.

As we discuss below, one of the conceptual bases of our approach comes from considering greenhouse gas stabilisation. Stabilising the atmospheric concentration of methane requires capping the ongoing emissions, while a number of recent studies (Matthews and Caldeira, 2008; Matthews et al., 2009; Allen et al., 2009) describe CO_2 stabilisation in terms of a ‘carbon budget’ – a cap on integrated CO_2 emissions. In these terms our approach to methane offsets represents a trade-off between the two different types of ‘cap’. Recently, Smith et al. (2012) have discussed such a ‘mixed metric’ for stabilisation covering, at the expense of a degree of approximation, a wide range of gases. This work is discussed in more detail below.

The layout of the remainder of this paper is as follows. Section 2, which is primarily a review of earlier studies, describes the GWP as a metric for emission equivalence, noting the impossibility of having a single metric that captures all aspects of human influence on climate. Section 3 presents our proposal for an alternative to emission equivalence metrics: that methane offsets should be based on comparing on-going methane emissions (or reductions) to one-off emissions (or reductions) of CO_2 . We suggest that this avoids a number of the problems that have been identified with GWPs and that it can be regarded as a refinement and clarification of earlier ideas. Section 4 discusses our proposal from the perspective of off-setting methane emissions from rangeland cattle production. Our concluding section looks at the broader implications of our analysis within national and global efforts to mitigate anthropogenic global warming. Appendix A summarises a range of different metrics that have been proposed for comparing greenhouse gases.

2. Metrics for emissions

The various factors that induce climate change are often quantified in terms of radiative forcing. While a range of definitions exist (Hansen et al., 1997), the common aspect is the perturbation in the earth’s energy balance (generally expressed in W m^{-2}), most commonly defined at the tropopause. In general circulation models (GCMs), radiative forcing is a diagnostic quantity – a ‘summary statistic’ that characterises the result of processes that the model calculates in more detail. Simple climate models commonly use radiative forcing as a way of making such models emulate the behaviour of GCMs. We denote the incremental forcing per unit

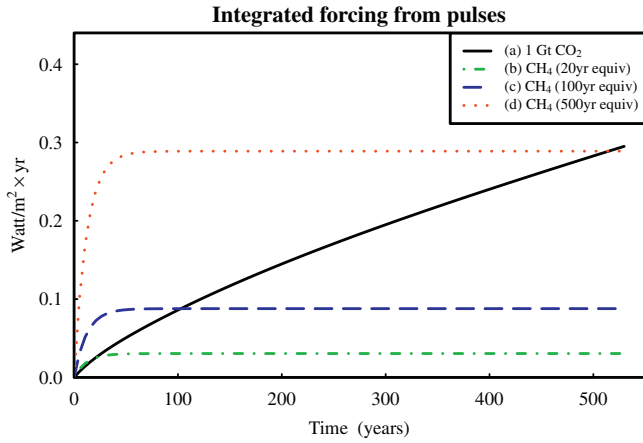


Fig. 1. Integrated radiative forcing for pulses (a) of CO₂ (black solid line, from Eq. (2.3)) and (b) for CH₄ scaled by GWPs for 20 (green chain), (c) 100 (blue dashed) and (d) 500 (red dotted) years (from Eq. (2.4)). These curves also correspond to the instantaneous effect of ongoing constant sources.

mass of gas X as a_X , noting that a_{CO_2} and a_{CH_4} actually depend on the respective concentrations of these gases.

As noted in Section 1, a number of metrics have been proposed for comparing emissions of the different greenhouse gases. While some of the alternatives are noted below, it is the global warming potential (GWP) that has achieved most use and which is used in the Kyoto Protocol.

The GWP is defined in terms of integrals of perturbations in radiative forcing. It is commonly calculated using response functions, R_X , which give (in a linear approximation) the proportion of a pulse of gas X remaining in the atmosphere after time t . These responses are derived from models and are often approximated by simple mathematical parameterisations.

Thus the effect of a pulse of size Δ_X at time t_0 is the perturbation $\delta_X(t) = \Delta_X(t_0)R_X(t - t_0)$. Response functions also describe the mass perturbation, $\delta M_X(t)$, from ongoing emissions, $E_X(t')$, as: $\delta M_X(t) = \int_0^t R_X(t - t')E_X(t')dt'$.

The definition of the GWP for gas X and time horizon τ is:

$$\text{GWP}_{X:\tau} = \frac{\int_0^\tau \delta F_{X:\text{pulse}}(t) dt}{\int_0^\tau \delta F_{\text{CO}_2:\text{pulse}}(t) dt} = \frac{a_X \int_0^\tau R_X(t) dt}{a_{\text{CO}_2} \int_0^\tau R_{\text{CO}_2}(t) dt} \quad (2.1)$$

For the purposes of our subsequent analysis, it is helpful to write the GWP in terms of time-averaged responses $\langle R_X(t) \rangle_\tau = \int_0^\tau R_X(t) dt / \tau$ as

$$\text{GWP}_{X:\tau} = \frac{a_X}{a_{\text{CO}_2}} \frac{\tau \langle R_X(t) \rangle_\tau}{\tau \langle R_{\text{CO}_2}(t) \rangle_\tau} = \frac{a_X}{a_{\text{CO}_2}} \frac{\langle R_X(t) \rangle_\tau}{\langle R_{\text{CO}_2}(t) \rangle_\tau} \quad (2.2)$$

The decline of a pulse of methane can be described by an exponential decay with a 'perturbation lifetime' or 'adjustment time' which is estimated to be 12 years and defines $R_{\text{CH}_4}(t) = \exp(-t/\tau_{\text{CH}_4:\text{adjust}}) -$ see discussion below, and also Fig. 15.1 of Enting (2002) from which the equations are taken.

For methane, the GWP is reported in the IPCC Fourth Assessment Report (Forster et al., 2007, Table 2.14) as 72, 25 and 7.6 for time horizons of 20, 100 and 500 years, respectively. These GWP values include the indirect effects on tropospheric ozone and the contribution to stratospheric water vapour.

Fig. 1 shows the integrated radiative forcing that underlies the definitions of the GWP. The solid black curve shows

$$\int_0^\tau \delta F_{\text{CO}_2:\text{pulse}}(t') dt' = a_{\text{CO}_2} \int_0^\tau R_{\text{CO}_2}(t') dt' \times 10^{12} \quad (2.3)$$

where the factor 10^{12} converts forcing per kg CO₂ to forcing per Gt CO₂. This is proportional to the denominator of (2.1) plotted as a function of τ . The other curves show the integrated radiative forcing from methane pulses 'equivalent' to pulses of 1 Gt CO₂ with 'equivalence' defined by GWPs for various time horizons. These are proportional to numerators of (2.1) as functions of τ and are specified by:

$$\int_0^\tau \delta F_{\text{CH}_4:\text{pulse}}(t') dt' = \frac{a_{\text{CH}_4}}{\text{GWP}_{\text{CH}_4:\tau}} \int_0^\tau R_{\text{CH}_4}(t') dt' \times 10^{12} \quad (2.4)$$

for $\tau = 20$ (green dotted), 100 (red dashed) and 500 (orange chain) years. As is implied by the definition of GWP, the integrated CO₂ forcing curve crosses the various methane curves at the time horizon for the respective GWPs that are used to scale the emission-equivalence. The large differences away from the points of intersection illustrate that the use of this approach to define emission-equivalence leads to large differences in the time dependence of the forcing. Thus for equivalence defined by the 100-year GWP, reducing methane rather than the 'equivalent' CO₂ gives a short-term benefit but incurs an ever-increasing long-term penalty. Conversely reducing CO₂ rather than methane is significantly less advantageous in the short term but advantageous in the long term. This is even more apparent if one considers radiative forcing rather than its integral. For equivalence defined by the 500-year GWP the same considerations play out on longer timescales. The case of the 20 year GWP is rather different. Reducing methane emissions rather than CO₂ is again disadvantageous in the long-term but in this case gives little benefit in the short term. This is because the rapid decline in the methane response is matched by the initial decline in the CO₂ response, resulting from the fast processes in the carbon cycle.

O'Neill (2000) described some of the history of the GWP concept in an editorial overview of two papers: Smith and Wigley (2000a) which analysed the trade-offs over time for various choices of time-horizon and the companion paper (Smith and Wigley, 2000b) which looked at the uncertainties in the numerical values of GWPs as metrics of climate change, noting the non-linearities in the forcing relations $F_X = f_X(C_X)$, and the issues of timing. Shine et al. (2005a) have defined the 'global temperature change potential' (GTP) as an alternative.

More recently Shine (2009) has re-visited the history of the GWP concept, and revived the idea of a metric that includes mitigation costs. We note that since the climate influence of the long-lived greenhouse gases is essentially global while costs are likely to have local differences, it seems to us to be desirable to keep climatic and economic aspects separate so that, within a global target, trade-offs between gases can be made in order to minimise local costs by either mitigation or trading. As we note in Appendix A, a number of the proposals for metrics that incorporate economic factors are a response to the inconsistencies in having targets set in terms of GWPs.

As noted in Section 1 the response of pulse perturbations of methane can be described by a single exponential decay, but not at the rate determined by λ^{-1} , the mean lifetime (or turnover time). Rather, the timescale for exponential decay, termed the 'effective lifetime', is longer than the bulk turnover time (Prather, 1994, 1996). The generic relations are given by Eqs. (15.1.1c,e,f) in Enting (2002) as:

$$\frac{d}{dt} M_{\text{CH}_4} = E_{\text{CH}_4}(t) - \lambda(M_{\text{CH}_4})M_{\text{CH}_4} \quad (2.5)$$

so that a perturbation about a reference $M_{\text{CH}_4}(t) = M_{\text{CH}_4:\text{ref}}(t) + \delta_{\text{CH}_4}(t)$ is described by

$$\frac{d}{dt} \delta_{\text{CH}_4}(t) = -\lambda(M_{\text{CH}_4:\text{ref}}(t))\delta_{\text{CH}_4} - M_{\text{CH}_4:\text{ref}}(t) \frac{\partial \lambda}{\partial M} \delta_{\text{CH}_4} \quad (2.6)$$

The adjustment time (given by the inverse of the coefficient of δ_{CH_4} in (2.6)) is therefore

$$\tau_{\text{CH}_4:\text{adjust}} = \left(\lambda(M_{\text{CH}_4:\text{ref}}(t)) + M_{\text{CH}_4:\text{ref}}(t) \frac{\partial \lambda}{\partial M} \right)^{-1} \quad (2.7)$$

Similar considerations apply for the case of a constant perturbation from an additional ongoing source that leads to a constant perturbation of the methane concentration (or mass) in the atmosphere.

$$\begin{aligned} \frac{d}{dt} \delta_{\text{CH}_4}(t) &= \delta E_{\text{CH}_4:\text{ongoing}} - \lambda(M_{\text{CH}_4:\text{ref}}(t)) \delta_{\text{CH}_4} \\ &\quad - M_{\text{CH}_4:\text{ref}}(t) \times \frac{\partial \lambda}{\partial M} \delta_{\text{CH}_4} = 0 \end{aligned} \quad (2.8)$$

giving

$$\delta_{\text{CH}_4} = \delta E_{\text{CH}_4:\text{ongoing}} \cdot \tau_{\text{CH}_4:\text{adjust}} \quad (2.9)$$

Since the loss rate, λ , decreases with concentration, $\partial \lambda / \partial M$ will be negative and so $\tau_{\text{CH}_4:\text{adjust}}$ will be longer than the turnover time $\lambda(M_{\text{CH}_4:\text{ref}}(t))^{-1}$, but still much shorter than the characteristic timescales of CO_2 .

Assessing the role of methane in mitigating climate change entrains many of the issues of trade-offs over time between prompt vs delayed action. The arguments for prompt action are to reduce ongoing impacts and to increase the chance of avoiding tipping points (Lenton et al., 2008). Arguments for delayed action include allowing time to develop better mitigation technology (Wigley et al., 1996). Analysis of such inter-temporal trade-offs has many similarities to the analysis of temporary sequestration. Temporary sequestration is seen as a response to the concerns above – dealing with immediate threats, while ‘buying time’ for more sustainable mitigation. It becomes a question of intergenerational equity: temporary storage forces the problem of the future emissions onto future generations. Temporary storage may also create additional problems in future, as the planet may be less able to cope at the time emissions are released, when closer to saturation of ocean and biosphere sinks – so in fact we may not buy time through temporary storage. The role of temporary storage has been considered in several studies (Dobes et al., 1998; Kirschbaum, 2003; Herzog et al., 2003).

Much confusion and controversy arises when these considerations are applied to CO_2 vs CH_4 as trade-offs for mitigation (Boucher, 2012, and references therein). For example Enting et al. (2008) argue that for a consistent approach to greenhouse gas stabilisation, one should adopt equivalence based on 500-year GWPs (thus emphasising reductions in CO_2). In contrast, it is sometimes argued (e.g., Russell et al., 2008) that the 20-year GWP should be used in order to encourage prompt reductions in methane emissions. The example from Reilly et al. (1999) noted above implies that some inclusion of CH_4 is desirable: the less effective ‘ CO_2 -only’ case is equivalent to assigning a GWP of zero for CH_4 .

The discussion above, comparing the solid black (CO_2) and dotted green (CH_4 with equivalence defined by GWP of 72) in Fig. 1 shows the flaw in proposals for using a GWP of 72 to encourage prompt reductions in methane emissions. Within a trading scheme with emission equivalence, using a GWP of 72 means that reducing emissions of CH_4 rather than CO_2 gives ‘break-even’ after 20 years (and little net benefit up to 20 years) with increasingly negative impacts thereafter.

3. An alternative methane metric

As noted in Section 1, we propose that, when considering offsetting methane emissions, it is appropriate to compare on-going

methane emissions to one-off removals of CO_2 . Our main focus is on the use of CO_2 removal (carbon sequestration) to offset methane emissions. Our proposal is based on the following approximation, which can be tuned so that it holds over a wide range of timescales:

$$\begin{aligned} \delta F_{\text{CO}_2:\text{pulse}}(t) &\approx \delta F_{\text{CH}_4:\text{ongoing}}(t) \\ &\Rightarrow a_{\text{CO}_2} \cdot \Delta_{\text{CO}_2} \cdot R_{\text{CO}_2}(t) \\ &\approx a_{\text{CH}_4} \cdot E_{\text{CH}_4:\text{ongoing}} \int_0^t R_{\text{CH}_4}(t') dt' \end{aligned} \quad (3.1)$$

If we choose an appropriate timescale, t^* , which is significantly greater than the atmospheric lifetime of methane and denote $R_{\text{eff}} = R_{\text{CO}_2}(t^*)$ we can write the expression (3.1) as

$$a_{\text{CO}_2} \Delta_{\text{CO}_2} R_{\text{eff}} \approx a_{\text{CH}_4} \cdot E_{\text{CH}_4:\text{ongoing}} \cdot \tau_{\text{CH}_4:\text{adjust}} \quad (3.2)$$

To apply this approximation, we may express either the equivalent ongoing methane emissions in terms of the pulse emission of CO_2 :

$$E_{\text{CH}_4:\text{ongoing}} = \frac{a_{\text{CO}_2}}{a_{\text{CH}_4}} \frac{R_{\text{eff}}}{\tau_{\text{CH}_4:\text{adjust}}} \Delta_{\text{CO}_2} \quad (3.3)$$

or the converse:

$$\Delta_{\text{CO}_2} = \frac{a_{\text{CH}_4}}{a_{\text{CO}_2}} \frac{\tau_{\text{CH}_4:\text{adjust}}}{R_{\text{eff}}} E_{\text{CH}_4:\text{ongoing}} \quad (3.4)$$

The conversion factors are more conveniently used in terms of carbon mass, giving 1.1 t C (4.07 t CO_2) offsetting 1 kg CH_4 per year with $R_{\text{eff}} = 0.3$.

With this conversion, approximation (3.1) proves to be quite accurate if $R(t)$ is changing relatively slowly in the vicinity of t^* . The choice of R_{eff} defines the rate of ongoing methane emissions which are ‘equivalent’ to one-off sequestration of 1 Gt of CO_2 . Larger values of R_{eff} mean more weight is given to the effect of CO_2 on radiative forcing, and so the rate of ‘equivalent’ CH_4 emissions must be correspondingly higher, giving 0.95 t C (3.5 t CO_2) offsetting 1 kg CH_4 per year if R_{eff} is set to 0.35.

If t^* is sufficiently large for R_{CO_2} to be slowly varying, so that $R_{\text{CO}_2}(t^*)$ is close to the average, the ratio of the CO_2 pulse to ongoing CH_4 can be approximated as

$$\frac{\Delta_{\text{CO}_2}}{E_{\text{CH}_4:\text{ongoing}}} \approx \frac{a_{\text{CH}_4}}{a_{\text{CO}_2}} \frac{\langle \int_0^t R_{\text{CH}_4}(t') dt' \rangle_{t^*}}{\langle R_{\text{CO}_2}(t) \rangle_{t^*}} \quad (3.5)$$

Thus compared to the definition of GWP (as expressed in (2.2)) we are considering the average effect of a pulse of CO_2 as for GWP, but comparing it to the average effect of ongoing methane emissions, which is given by the average of the **integral** of the methane response function.

The comparison of the two sides of the approximation in (3.1) is shown in Fig. 2, where we introduce two different cases for one-off emissions of CO_2 , and two choices of R_{eff} for ongoing CH_4 emissions. For the one-off CO_2 emission we consider an instantaneous 1 Gt pulse of CO_2 at $t = 0$, and a lagged release of 1 Gt of CO_2 with an e -folding time of 40 years. This gives an emission rate of $\exp(-t/40)/40$ in Gt CO_2 per year. For ongoing CH_4 emissions we use Eq. (3.3) to define ‘equivalent’ emissions to one-off emissions of CO_2 , choosing $R_{\text{eff}} = 0.3$ and $R_{\text{eff}} = 0.35$. It will be seen from Fig. 2 that the radiative forcing from a pulse of CO_2 and ongoing emissions of CH_4 differs relatively little over a range of multi-century timescales. Fig. 3 shows the time-integrated radiative forcing for the same cases.

Comparing this to Fig. 1 which shows the ‘equivalence’ from the Kyoto definition, it will be seen that the new metric is much

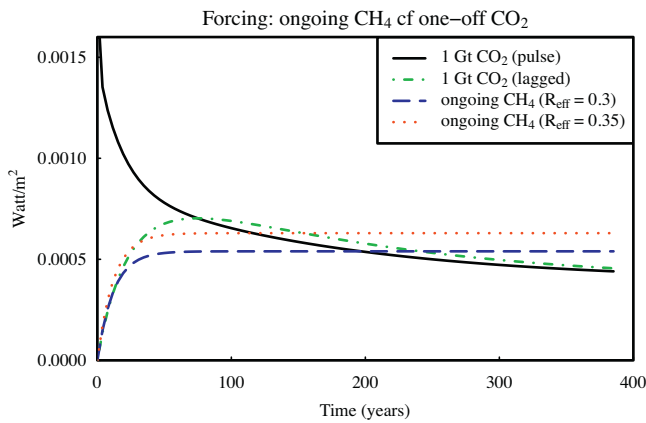


Fig. 2. Comparison of instantaneous radiative forcing of one-off CO₂ emissions and ongoing CH₄ emissions. The CO₂ releases are of 1 Gt CO₂ as an ‘instantaneous’ pulse (solid black line) or as an exponentially decaying pulse with 40-year decay time (green chain curve). The ongoing methane releases are of 0.246 kg CH₄ per year (blue dashed curve) or 0.287 kg CH₄ per year (red dotted curve), representing $R_{\text{eff}} = 0.3$ and 0.35, respectively, in relation (3.3).

less dependent on an arbitrary choice of time horizon. A consequence of this is that assessments of the relative climate impacts of different mitigation trade-offs are less sensitive to climate model uncertainties.

In particular, if a one-off ‘instantaneous’ removal of CO₂ (the opposite of a pulse emission) is used to offset ongoing CH₄ emissions, as specified above, then there will be a net radiative benefit over the initial years and approximate break-even on an ongoing basis for long into the future. The ‘benefit’ in this ‘instantaneous’ case means that offsetting CH₄ emissions with a one-off removal of CO₂ using a sequestration process that accumulates carbon over time can still be beneficial as shown in the lagged case in Figs. 2 and 3. The closer agreement in the cases of ongoing methane emissions and lagged CO₂ removal means that assessments of the relative climate impacts of different mitigation trade-offs are even less sensitive to climate model uncertainties than in the case without the lag in CO₂ removal. Underlying the use of radiative forcing is the principle that equal radiative forcing over time will lead to equal temperature changes. This is found to be a good approximation in the case of well-mixed greenhouse gases. The specific 40-year e -folding time has been chosen to give this agreement. As

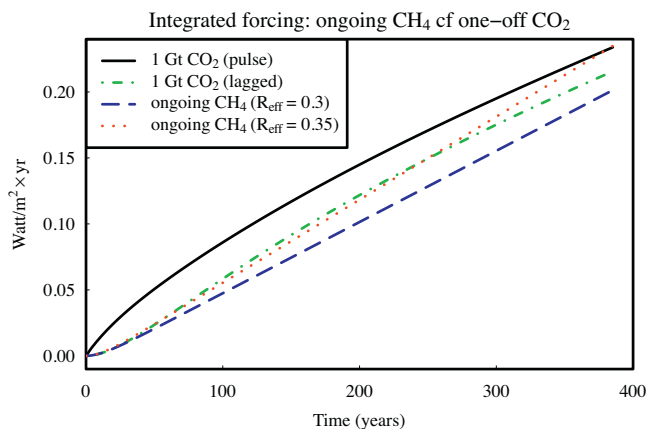


Fig. 3. Comparison of time-integrated radiative forcing of one-off CO₂ emissions and ongoing CH₄ emissions. The CO₂ releases are of 1 Gt CO₂ as an ‘instantaneous’ pulse (solid black line) or as an exponentially decaying pulse with 40-year decay time (green chain curve). The ongoing methane releases are of 0.246 kg CH₄ per year (blue dashed curve) or 0.287 kg CH₄ per year (red dotted curve), representing $R_{\text{eff}} = 0.3$ and 0.35, respectively, in relation (3.3).

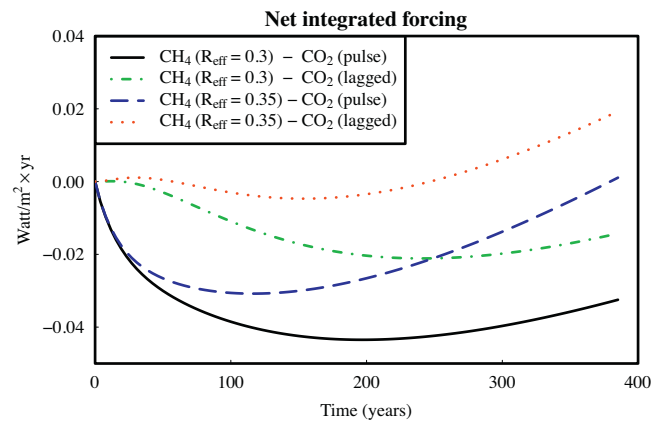


Fig. 4. Comparison of net time-integrated radiative forcing from using a one-off removal of 1 Gt of CO₂ to offset ongoing CH₄ emissions (i.e. differences of cases in Fig. 3). Instantaneous CO₂ removal with ongoing 0.246 kg CH₄ per year (solid black line); instantaneous CO₂ removal with ongoing 0.287 kg CH₄ per year (blue dashed curve); 40-year lagged CO₂ removal with ongoing 0.246 kg CH₄ per year (green chain curve); 40-year lagged CO₂ removal with ongoing 0.287 kg CH₄ per year (red dotted curve).

noted below, we can regard this as an approximate solution of the forcing equivalent index (FEI) approach of Wigley (1998). In terms of rate of vegetation growth, the 40-year e -folding time represents a minimum requisite growth rate. For species that grow faster than this, the 40-year e -folding time permits staged planting.

Figs. 2 and 3 show instantaneous radiative forcings and time-integrated radiative forcings, respectively, for a number of cases. To quantify the effect of using this new notion of ‘equivalence’ to specify offsets for CH₄ emissions, Fig. 4 shows the net radiative forcing when ongoing CH₄ emissions are offset by one-off carbon sequestration. The four cases represent the two forms of CO₂ offset (instantaneous or 40-year e -fold) combined with the two values (0.3 or 0.35) for R_{eff} . It will be seen that with $R_{\text{eff}} = 0.35$, the 40-year e -folding case gives a very close cancellation. The contrast between this approximate radiative equivalence and the GWP ‘equivalence’ relation is particularly striking.

Our original proposal for offsetting ongoing methane emissions with a one-off carbon sequestration was initially quantified in the ‘Lauder methane offset calculator’ (Nason, 2010). The main difference between the scale factor proposed in (3.3) and numbers in the ‘Lauder methane offset calculator’ is the factor R_{eff} which we propose should be in the range 0.3–0.35. The reason for this factor is that sequestering 1 Mt of carbon (MtC) does not result in a long-term lowering of atmospheric content by 1 MtC. This has commonly been misunderstood in the analysis of terrestrial sequestration (Enting, 2000). While our approach represents a somewhat radical departure from most current analysis, it actually has precursors in other recent studies. Thus we compare three earlier approaches that reach similar conclusions from somewhat different perspectives:

‘Budget-cap’ analysis Stabilising the human influence on temperature at some future time t_{stab} means stabilising radiative forcing, F , and this means stabilising the atmospheric concentrations of radiatively active substances. For CO₂, various studies (Matthews and Caldeira, 2008; Matthews et al., 2009; Allen et al., 2009) have pointed out that this means (approximately) capping the amount of cumulative CO₂ emissions, i.e. $\Delta M_{\text{CO}_2}(t > t_{\text{stab}}) \propto \int_{t_{\text{stab}}}^{t_{\text{stab}}} E_{\text{CO}_2}(t') dt'$. The analysis by Matthews et al. (2009) indicates

that the proportionality factor (which they call the ‘airborne fraction of cumulative carbon emissions’) is approximately 0.35 (Matthews et al., 2009, Fig. 2b). In considering a wider range of stabilisation profiles, Enting et al. (2008) found values ranging from 0.35 to 0.5 for the ‘airborne fraction of cumulative carbon emissions’.

We write this as

$$\Delta F_{\text{cap:CO}_2} \approx 0.35 a_{\text{CO}_2}(C_{\text{CO}_2}) \int_0^t E_{\text{CO}_2} dt \quad (3.6)$$

where the notation $a_{\text{CO}_2}(C_{\text{CO}_2})$ reflects the dependence of a_{CO_2} on concentration. In contrast (see Eq. (2.9)),

$$\delta F_{\text{cap:CH}_4} \propto \delta_{\text{CH}_4} = \tau_{\text{CH}_4:\text{adjust}} \cdot E_{\text{CH}_4:\text{ongoing}} \quad (3.7)$$

Recently, Smith et al. (2012) have proposed a division of greenhouse gases into long-lived, for which a budget cap is required in order to stabilise temperature, and short-lived, for which a cap on ongoing emissions is sufficient. Their analysis was expressed in terms of calculated temperature changes. For CO_2 they estimate 4.3×10^{-16} K/kg, while for CH_4 they estimate 1.74×10^{-12} K/(kg/year) (Smith et al., 2012, supplementary information). This implies that 1 kg/year CH_4 emission is being treated as equivalent, for the purposes of stabilising temperature, to CO_2 emissions of 4047 kg CO_2 or 1110 kg carbon. This close agreement with our results is to be expected, since the underlying considerations are very similar. Although Smith et al. (2012) quote uncertainty ranges for the values given above, these include the uncertainty associated with the temperature changes and these will be highly correlated between gases. Consequently, their quoted uncertainties cannot be translated into an uncertainty on the appropriate emission ratio for one-off CO_2 vs ongoing CH_4 .

Using 500-year GWPs Notionally, for stabilisation, an infinite timescale is required to ensure no change in forcing into the indefinite future.

A compromise proposed by Enting et al. (2008) was to use 500-year GWPs since these had been already calculated. They noted that this was not proposing actual planning over 500 years, but rather providing an assurance of the existence of sustainable trajectories beyond the end of this century.

Using this approach, a pulse Δ_{CH_4} of methane is attributed its integrated effect

$$\int_0^{500} F_{\text{CH}_4:\text{pulse}} dt = a_{\text{CH}_4} \cdot \tau_{\text{CH}_4:\text{adjust}} \cdot \Delta_{\text{CH}_4} \quad (3.8)$$

while a pulse Δ_{CO_2} of CO_2 is attributed

$$\begin{aligned} & \int_0^{500} F_{\text{CO}_2:\text{pulse}} dt \\ &= a_{\text{CO}_2} \Delta_{\text{CO}_2} \times \int_0^{500} R_{\text{CO}_2}(t') dt' \\ &= 500 \langle R_{\text{CO}_2} \rangle_{500} \cdot a_{\text{CO}_2} \cdot \Delta_{\text{CO}_2} \end{aligned} \quad (3.9)$$

where $\langle R_{\text{CO}_2} \rangle_{500}$ is the average CO_2 response over the 500-year period.

Equating (3.8) and (3.9) and then spreading this methane pulse out over the 500 years (which makes little change to the integrated radiative forcing) gives

$$E_{\text{CH}_4:\text{ongoing}} = \frac{\Delta_{\text{CH}_4}}{500} = \frac{a_{\text{CO}_2} \langle R_{\text{CO}_2} \rangle_{500} \Delta_{\text{CO}_2}}{a_{\text{CH}_4} \tau_{\text{CH}_4:\text{adjust}}} \quad (3.10)$$

Using $\langle R_{\text{CO}_2} \rangle_{500}$ to approximate an effective response R_{eff} gives the new offset relation (3.3).

Of course, as is seen by comparing Figs. 3 and 1, the temporal pattern of radiative forcing of the new approach, compared to the ‘pulse’ definition used in the GWP is very different.

The FEI (forcing equivalent index) approach

As mentioned above, Wigley (1998) noted the possibility of solving the inverse problem which specifies determining an emission trajectory for one gas that exactly matches the radiative forcing from a specified emission trajectory for another gas. The relation between the emissions was expressed as the FEI. This approach has been applied by Manning and Reisinger (2011) in analysing stabilisation of radiative forcing. In particular, the example in their Fig. 1 shows a step-wise increase (or decrease) in ongoing methane emissions being exactly balanced by a decaying decrease (or increase) in CO_2 emissions. Their example does not give numerical details. Our analysis suggests that their argument can be applied more generally.

In considering the range of possible values for the scale factors given by relations (3.3) and (3.4), we need to distinguish scientific uncertainty from those aspects where the values reflect choices that are a matter of policy in selecting from a known range of variation. Thus the choice of the time t^* for matching the response function represents a value judgement, leading to a 10% range in the value of R_{eff} — this is of course small compared to the range of over 100% associated with the choice of time horizon when defining equivalence through GWPs. The radiative effectiveness a_{CO_2} is concentration dependent, as is a_{CH_4} to a lesser extent. This raises the issue of whether the equivalence should use fixed a_{CO_2} (corresponding to time of sequestration) or whether a_{CO_2} should evolve with the atmospheric CO_2 (thus reducing allowed CH_4 emission). Choosing the appropriate way to attribute non-linear effects is a generic problem. Various formalisms for attributing non-linear effects have been explored by Trudinger and Enting (2005). We

emphasise their conclusion: these are policy choices for which there can be no unambiguous scientific answer.

The scientific uncertainties can be assessed by considering the factors in (3.3) and (3.4) individually. Uncertainties in R_{eff} reflect uncertainties in the response R_{CO_2} . There has recently been an extensive intercomparison study of CO_2 response (Joos et al., 2012) which reported a wide range of values. However much of this range can be attributed to non-linear effects since the intercomparison specified calculations with large pulse releases. A more appropriate measure of the long-term response would be of order 10% based on the uncertainty in the long-term budget, which is dominated by uncertainties about the contribution of land-use change to the observed 20th century CO_2 increase. The perturbation lifetime for the methane response is a theoretical construct, with values estimated from chemical models. There has been no definitive detection of the associated change in OH (Forster et al., 2007, Section 2.3.5). Prather et al. (2001) (Table 4.3) give a range of model results which imply about a 5% uncertainty in $\tau_{\text{CH}_4:\text{adjust}}$. Forster et al. (2007) reported uncertainties of order 10% in the radiative transfer calculations used to determine a_{CO_2} and similar uncertainty in a_{CH_4} (Forster et al., 2007, Table 2.12).

4. Application

Methane emissions from livestock make a significant contribution to the globally integrated change in radiative forcing due to anthropogenic emissions. The importance of such emissions relative to CO_2 will vary greatly from nation to nation as do agricultural systems. In this section we use Australian rangelands to demonstrate the application of our approach to quantifying offsets for methane emissions from livestock.

Livestock emissions, primarily CH_4 and N_2O , are estimated to account for 8–11% of global anthropogenic greenhouse gas emissions using 100-year GWP-based comparisons. About half of this is CH_4 , predominantly produced as a by-product of microbial activity in ruminant digestion (O'Mara, 2011). However, animal agriculture is an important resource globally providing multiple benefits to societies, particularly those in developing countries. Simply reducing stock numbers to mitigate climate change is not compatible with sustainable land management or food security goals and is inconsistent with the UNFCCC objective that stabilisation of greenhouse gas concentrations should be achieved in a way that does not threaten food production (UNFCCC Article 2, 1992). In addition, as with any case of achieving mitigation by reducing production, there is the risk that stock reductions in one nation would lead to increases in stocking in other nations.

In ruminant animals enteric methane production is a mechanism that effectively removes hydrogen from the rumen, enabling efficient fermentation of feed and transfer of energy via microbial activity to the animal for maintenance, growth and milk production. Some methane is also produced from dung and urine. Despite considerable investment in research, there is currently limited potential for substantially reducing methane emissions from livestock (McAllister et al., 2011; Henry et al., 2012) without a negative impact on animal performance. Hence, in the short to medium timescale, methane emissions are likely to be mitigated more effectively via offsetting than by emission reduction strategies.

The methane offset metric proposed here can be applied to calculate the quantum of CO_2 that must be removed from the atmosphere in order to neutralise the increase in radiative forcing due to ongoing management of ruminant livestock production.

Here we provide an overview of possible offsets for livestock enterprises to illustrate applications.

We take as an example, beef cattle production in northern Australia where *Bos indicus* (and *Bos indicus* cross) animals are

typically grazed on native grasses at stocking rates of about 10 ha/beast. Annual methane emissions would be around 5.5 kg CH_4 per ha (Eckard et al., 2010). In this case, using our approach, an estimated sequestration of 6.1 t of carbon per hectare is required to offset the radiative forcing due to cattle grazing, assuming a long-term effectiveness factor of $R_{\text{eff}} = 0.3$. (Note that expressions (3.3) and (3.4) are expressed in terms of mass of CO_2 , which is 3.67 times the carbon mass.)

In the extensive grazing systems example, offsets could potentially be provided through reforestation (new tree plantings or allowing regrowth to establish through to maturity), revegetation (e.g. saltbush or other browse shrubs), or soil carbon sequestration. The potential to implement these options is considered briefly below, but a discussion of the economic viability of offset options is not included here.

In the case of reforestation offsets, assuming a carbon mass of 50% dry matter in wood means that 12.2 t DM (tonnes of dry matter) would provide the offset of 6.1 t C per ha managed for cattle as estimated above. Typical tree basal areas in north eastern Australian woodlands are around 10 m^2/ha (Burrows et al., 2002) which translates to 60 t DM/ha. Hence, 0.2 ha new tree plantings would be required to offset each ha rangeland stocked at 10 ha/beast. Thus the radiative forcing due to average annual methane emissions of 55 kg CH_4 per adult equivalent beast in northern Australia could be offset at the rate of 60 kg of carbon sequestered (range 55–60 kg – see Figs. 2 and 3) and this could be achieved with one-off environmental plantings (or woodland regeneration) of 2 ha per beast – i.e. 20% of the area.

The possibilities for offsets from changes in soil carbon depend on the location. At a soil carbon concentration of 0.5% as might be expected for better soils in north-eastern Australian rangelands, there would be 30 t C/ha in the top 30 cm (Krull and Bray, 2005). Sequestering 6.1 t C/ha is therefore equivalent to increasing the mass of soil C by 20% or increasing the soil C content from 0.5% to 0.6% in the 0 to 30 cm layer, noting that there will be a large range in the potential to increase soil carbon, depending on soil type, climate and management options. The additional carbon would then have to be above the initial (pre-management) level and would have to be retained and not re-released to the atmosphere. High climate variability characteristic of tropical and sub-tropical semi-arid rangelands and typically fragile low-nutrient soils make building soil carbon challenging, but it may be practical in previously degraded landscapes. Combinations of offsets e.g. practices to build soil carbon and tree plantings may be an effective risk management strategy for retaining sequestered carbon in the landscape.

As noted previously, the climatic influence of long-lived greenhouse gases is global, and so the spatial location of offsetting actions has virtually no influence on the climatic impact. However, we have focused on offsets within a single agricultural production unit for a number of reasons – most of these focus on issues of transparency. Within a single unit it is easier to ensure that there is no double counting and issues of 'ownership' and 'attribution' should be clearer. Similarly, greater transparency should be possible with respect to any requirements for 'additionality', if offsets are required to be achieved through activities that are additional to existing practice.

One of the disadvantages of undertaking offsets within a single agricultural unit is the absence of mechanisms to spread risk such as the loss of the sequestered carbon due to drought, fire, etc. Another disadvantage is that the sequestration strategy possible on any single agricultural unit may not represent the least-cost option that would be found in a broad market-based mechanism.

In illustrating the application in a rangeland grazing situation, it is clear that there will be a degree of uncertainty in the calculation of offsets due to both spatial and temporal variations. The latter is

associated primarily with climatic or seasonal variability. The scale of variation within and between landscapes affects the sampling intensity and measurement protocols that would be required to verify soil carbon sequestration (Pringle et al., 2011) and hence the costs of demonstrating an offset.

An additional consideration for a single agricultural unit is the feasibility of ensuring that the growth in carbon stocks (sequestration) is in excess of an increase in stocking rate so that there is in reality a decrease in net global warming impact. This becomes largely an economic question and although it is, like the uncertainty characteristics above, largely independent of the metric used it remains a significant practical consideration.

In comparing the implications of using our approach as an alternative to determining offsets using GWP-based emission equivalence, much of the comparison is independent of the illustrative numbers above. Using $R_{\text{eff}} = 0.35$, we have 1 kg CH₄ per year offset by one-off uptake of 950 kg C, i.e. 3500 kg CO₂. Using a GWP of 25, emitting 1 kg CH₄ per year needs to be offset by emission reductions of 25 kg CO₂ per year and so 140 years are required to achieve a net benefit, even in the absence of discounting considerations. Similarly, using a GWP of 72, emitting 1 kg CH₄ per year needs to be offset by emission reductions of 72 kg CO₂ per year and so 49 years are required achieve a net benefit. However, our 40-year lagged form has $87 \times e^{-t/40}$ kg CO₂ per year removal in this case our approach takes 43 years to drop below the GWP=25 case, but just over 8 years to drop below the GWP=72 case and after 36 years is just under half what would be required under emission-equivalence defined in terms of GWPs with 20 year time horizon.

Our approach for offsetting methane emissions is far more costly than using 100-year GWPs under a conventional approach. This reflects the well-known inadequacies of such emission-equivalence. What our analysis shows is that proposals to address these inadequacies by applying a 20-year GWP greatly over-compensate for methane emissions in a relatively short time.

These timescale comparisons do not depend on the actual values for stocking rates or carbon sequestration potential and do not depend on whether CO₂ offsets are used to balance all or only part of the emissions from cattle grazing.

5. Discussion

In Section 3 we have proposed an alternative to ‘emission-equivalence’ that offsets on-going methane emissions with a one-off removal of CO₂ and defines an appropriate scaling (Eqs. (3.3) and (3.4)). Fig. 3 shows that this gives a close equivalent radiative forcing over a wide range of times (unlike the GWP-based emission-equivalence using the relations shown in Fig. 1). Measures based on radiative forcing provide an appropriate compromise between relevance for impacts vs relative certainty. Our approach reduces the differences between short-term and long-term ‘equivalence’ for comparisons of CO₂ and CH₄. We achieve a good approximation to radiative equivalence over a range of timescales in a framework that is conceptually much simpler than solving the inverse problem for exact radiative equivalence as proposed by Wigley (1998) — see also Manning and Reisinger (2011).

One issue that we have not discussed (except for the case of the effective lifetime) is the role of non-linearity. Considerations of attributing responsibility for an effect that depends non-linearly on the cause can be done in a number of ways. Trudinger and Enting (2005) have described a number of formulations in the context of the so-called ‘Brazilian proposal’ for setting mitigation targets. They note that deciding between the different possibilities will be a political decision — there is no unique ‘correct’ answer determined by the science. Of the non-linearities that influence our

analysis, the most important is the non-linear relation $f_{\text{CO}_2}(C_{\text{CO}_2})$ that gives the amount of radiative forcing from CO₂. Other possible, but poorly quantified non-linearities can arise from climate feedbacks onto the biogeochemical cycles of methane and carbon dioxide. In the context of a specific pathway to stabilisation, our approach can be modified by replacing $b_{\text{CO}_2} R_{\text{eff}}$ by an average value of $(\partial/\partial C)f_{\text{CO}_2}(C_{\text{CO}_2}(t)) R_{\text{pert}}(t)$ with $C_{\text{CO}_2}(t)$ following a specified pathway and $R_{\text{pert}}(t)$ defined as a response to perturbations about that pathway.

Our analysis shows that the approach of offsetting on-going methane emissions by a one-off removal of CO₂ is relatively insensitive to the choice of ‘equivalence time’ and thus avoids the situation where the choice between mitigation of CH₄ vs CO₂ implies a choice of ‘trade-offs’ between prompt and delayed action. Under our approach notionally ‘equivalent’ choices lead to similar trajectories of radiative forcing. This is unlike the cases considered by Reilly et al. (1999) where GWP-based ‘equivalence’ led to quite different outcomes. The similarity in radiative forcing means that projected temperature consequences of such offsetting will be less dependent on climate model uncertainty. Choice between prompt action to avoid tipping points (some of which may have already been passed) vs delay to wait for new technology (Wigley et al., 1996) can then be divorced from issues of which gases will be the most effective targets for mitigation.

We can think about the implications of using our new approach from the point of three contexts and levels of agents:

- (i) Agents seeking to assess/minimise impact on climate and compare alternative actions. (‘Agents’ may include farmers, businesses, nations);
- (ii) Agents doing this within context of emissions tax/trading defined in terms of GWP-based ‘emission equivalence’;
- (iii) The global community trying to mitigate climate change.

In operation for case (i), our approach could have carbon sequestration converted to a ‘conditional licence to emit’ methane. This would expire if the sequestered carbon was not maintained, but should not incur any additional penalty if the release of CO₂ takes place over timescales comparable to lagged removal that we analyse. The opposite exchange, in which an emission of CO₂ requires a permanent reduction of on-going methane emission, suffers from very severe challenges in managing the risk of non-compliance.

We believe that the new approach is a useful way of addressing the well-known inadequacies of using 100-year GWPs. In contrast, addressing these inadequacies by using emission-equivalence based on the 20-year GWP would impose an unjustified penalty on methane emissions and also fail to deliver climate benefits. Our approach seems particularly useful for the case of rangeland grazing where, as discussed in Section 4 the scope for direct mitigation of methane emissions is limited. We assert that such an approach could be useful for (iii), the global community, but that integrating this approach with other methane mitigation actions could be difficult. Of course, even if adopted as a global principle, such offsetting would be practical only for a small proportion of anthropogenic methane emissions. Indeed our approach is likely to be feasible for only a modest proportion of methane emissions from cattle.

Difficulties, which are economic and regulatory rather than scientific, arise for group (ii), for example Australian farmers operating within a conventional GWP-based trading scheme. Similar considerations could apply to any nation that tried to go-it-alone and use this approach internally while subject to a GWP-based international agreement. However, such an analysis of the desirability of wider application of our approach to offsetting methane emissions goes beyond the scope of the paper.

Also beyond the scope of any detailed analysis in this paper is the question of whether this mixed-metric approach is of wider

applicability in considering other short-lived climate forcings. Such issues are of current concern (Shindell et al., 2012, for example), particularly for emissions from aviation (Azar and Johansson, 2012, for example). As described above, Smith et al. (2012) applied the concept of comparing on-going emissions of short-lived gases against cumulative emissions of long-lived gases. However, their analysis was in the context of approaching stabilisation via a set of Representative Concentration Pathways (RCPs) (Meinshausen et al., 2011). The (Smith et al., 2012) analysis was confined to gas emissions and methane was by far the most important of these. If one considers forcing agents that act on shorter timescales, the concept of a single radiative forcing index as a measure of climate forcing starts to break down. Short atmospheric residence times lead to disparate spatial distributions since the agents do not have time to become well-mixed. This leads to disparate influences on climate. Nevertheless, there is clearly scope for further exploration of this issue.

Our focus has been on developing an approach which (a) reduces some of the arbitrariness associated with the use of GWPs for defining CO₂ equivalence; (b) meets the needs of rangeland agricultural systems; and (c) adds the scope for greater transparency in offsetting methane emissions. Nevertheless, the issue of going beyond GWP-based emission equivalence is firmly on the scientific agenda (Wigley, 1998; O'Neill, 2000; Shine, 2009; Manning and Reisinger, 2011). The discrepancies are particularly severe when analysing stabilisation (Daniel et al., 2012; Smith et al., 2012). Since our approach greatly reduces some of the anomalies associated with the use of GWPs we would expect that the approach that we have outlined here would be broadly consistent with any improved characterisation of greenhouse gas equivalence that might be adopted in future.

Notation

Values cited as from AR4 are from (Forster et al., 2007, Table 2.14) or from (Forster et al., 2007, Section 2.10.3.1) for indirect effects of methane.

$\langle \dots \rangle_{\tau}$	Time average over interval $[0, \tau]$.
a_X	The radiative forcing per unit mass (1 kg) for gas X . For consistency in our numerical calculations we relate mass to mixing ratio using the factor 0.471 ppm per GtC and write $a_X = b_X \times 0.471 \times 10^{-12} \times 12 / \mu_X$ in units of W m^{-2} per kg of gas X .
b_X	The incremental radiative forcing for gas X per unit of mixing ratio. Thus $b_X = (\partial / \partial C_X) f_X(C_X)$. We use $b_{\text{CO}_2} = 1.4 \times 10^{-2} \text{ W m}^{-2} \text{ ppm}^{-1}$ as used in AR4. We take b_{CH_4} as the sum $b_{\text{CH}_4:\text{direct}} + b_{\text{CH}_4:\text{indirect}}$ with $b_{\text{CH}_4:\text{direct}} = 3.7 \times 10^{-1} \text{ W m}^{-2} \text{ ppm}^{-1}$ and an indirect effect, mainly from stratospheric water vapour) as $b_{\text{CH}_4:\text{indirect}} = 0.4 b_{\text{CH}_4:\text{direct}}$ following AR4.
$C_X, C_X(t)$	Mixing ratio, often termed (incorrectly) the concentration, of gas X in the atmosphere (at time t).
$E_X, E_X(t)$	Emission rate for gas X (at time t).
$f_X(C_X)$	Functional relation specifying radiative forcing from gas X as a function of (mean) mixing ratio in the atmosphere.
$F_X, F_X(t)$	Radiative forcing from gas X in the atmosphere (at time t). Thus $F_X(t) = f_X(C_X(t))$.
$\delta F_{X:\text{release}}(t)$	Perturbation in radiative forcing at time t from gas X .
$\text{GWP}_{X:\tau}$	Global warming potential (GWP) for gas X evaluated for time horizon τ . See Eq. (2.1).
$M_X, M_X(t)$	Mass of gas X in the atmosphere (at time t).
$R_X(t)$	Impulse response function for gas X : the proportion of gas X remaining in the atmosphere at time t after an initial release.

R_{eff}	Effective value of CO ₂ response function used in defining the offset relation between ongoing methane release and one-off CO ₂ sequestration.
t	Time (in years).
$\delta_X(t)$	Time history of a perturbation in the mass of gas X in the atmosphere.
$\Delta_X, \Delta_X(t)$	The size of a pulse release of gas X (at time t).
μ_X	Molecular weight of gas X .
τ	Time horizon used in the definition of GWP.
τ_X	The atmospheric lifetime of gas X .
$\tau_{\text{CH}_4:\text{adjust}}$	Adjustment time-scale for methane perturbations – see Eq. (2.7). We use $\tau_{\text{CH}_4:\text{adjust}} = 12$ years as used in the IPCC TAR (Prather et al., 2001) and also used in AR4.
λ_X	Loss rate (inverse of turnover time) for gas X .

Note that in using these relations, care must be taken to ensure consistent units. In particular whether gases are described as concentrations (actually mixing ratio) or in mass units, (and for the case of CO₂ whether the mass is of carbon or of CO₂).

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A. Lauder, Carbon Grazing.
 J. Carter, Department of Science, Information Technology, Innovation and the Arts (Qld).
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Appendix A. Metrics for greenhouse gas emissions

As we have noted in Section 1, there is an extensive literature on metrics for greenhouse gases. In the body of the paper, we have concentrated on (a) the GWP because of its use in the Kyoto Protocol (b) a few of the studies that indicate the limitations of the GWP, and (c) studies that we regard as precursors of our approach. The broader aspects of metrics have been summarised in successive IPCC assessments, most recently by Forster et al. (2007). Fuglestedt et al. (2003) gives a more comprehensive review. A wide range of metrics has also been considered in the context of the so-called 'Brazilian Proposal' which involves national attribution of climate change (den Elzen et al., 2005).

As is common (e.g., Tol et al., 2012), we distinguish metrics based purely on physical criteria from those that combine both physical and economic criteria.

The *global warming potential* (GWP) is discussed in Section 2 as a metric for defining the relative importance of greenhouse gas emissions. Being based on integrated radiative forcing it is a purely physical metric that is expected to reflect temperature changes over the time horizon. However exactly what temperature effects are captured is somewhat uncertain. Variations that are noted by Fuglestedt et al. (2003) include using instantaneous radiative forcing, choosing the time horizon on the basis of investment timescales or replacing the fixed time horizon by discounted weighting into the future. The *global temperature change potential* (GTP) introduced by Shine et al. (2005b) compares gas emissions according to the temperature perturbation at a specified time. As a consequence of uncertainties in climate models, the values of GTPs are rather uncertain although the definition in terms of temperature is clear. Climate model uncertainty leads to the converse issue for GWPs where the values are relatively well known, but the climate implications are uncertain. Fuglestedt et al. (2003) note this issue in generic terms as a 'trade-off between certainty and relevance'. Shine et al. (2007) extended the GTP concept to have the time horizon vary according to a target date.

The forcing equivalence index FEI described by Wigley (1998) provides a degree of generality that avoids the arbitrariness inherent in the choice of time horizons on the GWP. We have noted this as a precursor of our approach – indeed our proposal corresponds to a special case in which a simple mixed metric corresponds closely to FEI-determined equivalence. As discussed below, this gives important simplifications when considering cost-based metrics.

Rather than seek fully general alternatives, Meinshausen et al. (2011) looked at the range of alternatives that had been developed as plausible future emission scenarios and proposed Representative Concentration Pathways (RCPs). Being based on scenarios, this approach has an implicit dependence on economic criteria.

There have also been many metrics based explicitly on economic considerations. Some of these considered an overall cost-benefit analysis with aims such as determining the overall global level of mitigation that would be appropriate. Such studies are beyond the scope of this summary. As noted by Tol et al. (2012), once the target is set, it is cost-effectiveness, not cost-benefit that becomes the relevant economic criterion.

More relevant to our proposal are cases where economic considerations are used to resolve anomalies that result from the problems with GWPs that were discussed in Section 2 (Johansson et al., 2006).

The general approach is to define a climate target, and cost functions for emission reductions over time. One then undertakes a constrained optimisation calculation to minimise the total cost (commonly with a discounting factor included) subject to meeting the climate target. A generic feature of the solutions of such calculations is that the shadow costs of alternative reduction actions shall be equal at all times (Tol et al., 2012). However for alternatives where exchanges between emissions use FEI-based equivalence, the problem simplifies. The target ceases to depend on the amount of such exchanges, regardless of the target, and the criterion of equal shadow costs follows directly from the extent to which the costs depend on the amount of exchange and is minimised when shadow costs are equal.

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