S1. Expansion of Metrics Discussion

In the main manuscript, we present an analysis of GWP timescales based on using an approach similar to the global damage potential methodology. Here, we expand on three topics: the compatibility of the GWP and most other metrics with stabilization targets, the richness of the literature considering global damage potentials including some papers which overlap in some aspects with the current manuscript, and a deeper discussion on the justifications presented for the use of short timescales.

Metrics and Stabilization

A number of authors have recognized that the GWP is not designed to achieve stabilization goals (Sarofim et al. 2005, Smith et al. 2012, Allen et al. 2016). Some actors (Brazil INDC, 2015) have claimed that certain metrics such as the Global Temperature Potential (Shine et al. 2005) or the Climate Tipping Potential (Jorgensen et al. 2014) are more compatible with a stabilization target such as 2 degrees C because they are temperature based. However, these metrics are also not designed to achieve stabilization goals, but rather to achieve a temperature target in a single given year. The challenge is that in any year after stabilization, any trading between emission pulses of carbon dioxide and a shorter-lived gas will cause a deviation from stabilization. For example, trading a reduction in methane emissions for a pulse of CO_2 emissions will lead to a near term decrease in temperature, but also a long-term increase in temperature above the original stabilization level.

One solution to the problem is a physically-based one. Allen et al. (2016) suggest trading an emission pulse of carbon dioxide against a sustained change in the emissions of a short-lived climate forcer. This resolves the issue of trading off what is effectively a permanent temperature change against a transient one. However, the challenge becomes one of implementation, as current policy structures are not designed for addressing indefinite sustained mitigation. Alternatively, a number of researchers (Daniel 2012, Jackson 2009, Smith et al. 2012) suggest addressing CO_2 mitigation separately from short-lived gases. Such a separation recognizes the value of the cumulative carbon concept in setting GHG mitigation policy (Zickfeld et al. 2009).

Another solution to this problem is to rely on optimized dynamic approaches (Manne & Richels 2001, Tanaka et al. 2010, Johansson 2012). In this case, the procedure is to derive optimal emissions paths from an integrated assessment model and then calculate the relative shadow price of different gases. The problem with this approach is that it is based on a theoretical calculation: in the real world, any difference between the integrated assessment model shadow prices and the real world abatement costs will cause the emissions of the gases to diverge from the chosen stabilization target.

The literature, as summarized above, demonstrates that any metric designed for exchanging emission pulses of a long-lived gas with a short-lived gas cannot be optimized for stabilization. However, these metrics can still be consistent with other methods of valuation, including damages.

Damage function analyses

We acknowledge that a number of authors have considered the use of relative damages as a potential metric, and in doing so have often compared the resulting global damage potential to the GWP. However, we believe that none of these papers has done so with the explicit goal of evaluating GWP timescales, and determining the discount rate implied by any given timescale choice.

We discuss some relevant papers here. Boucher (2012) in particular compares a global damage potential to the GWP_{100} with an uncertainty analysis, and finds, similar to our manuscript, that the median values of each approach are consistent with one another. Fuglestvedt et al. (2003), in an assessment of a number of different approaches to metrics, performed a similar calculation, and also found that a 100 year GWP was consistent with a discount rate on the order of 2%. De Cara et al. (2005), in an unpublished manuscript, also calculated the relationship between discount rates and time horizon, though they assumed linear damages.

Shindell et al. (2017) and Marten and Newbold (2012) have both used social cost approaches to determine relative value of gases. These approaches are valuable, but did not directly speak to the timescale issue. In order to do so, the approach used in this paper could be extended to incorporate valuation of agriculture (due to carbon fertilization and methane-derived ozone impacts) and human life (due to methane-derived ozone impacts). There is no a priori reason to expect that such an analysis would change the conclusions regarding timescales reached in our analysis.

Discussion of valuing near-term impacts:

As noted in the manuscript, several recent papers have suggested an increased focus on mitigation of short-lived climate forcers with the suggestion of using metrics with shorter timescales (Howarth et al. 2011, Ocko et al. 2017, Shindell et al. 2017,). These papers cite various benefits of near-term SLCF reduction such as reducing near-term rate of change, amplifying feedbacks, chances of exceeding tipping points in the near term, and reducing the probability of exceeding 2 degrees in the near term. These are all good goals, but the authors of these papers do not show why a short-term metric is the appropriate tool to reach these goals. The one quantitative justification of a timescale is the calculation that 25 years is the timeframe within which there is a 50% likelihood of exceeding 2 degrees warming. The problem with this logic is that while using a 25-year timescale might optimize the probability of not exceeding 2 degrees within 25 years, it would likely lead to an increased probability of exceeding 2 degrees (or the cost of remaining below that temperature) for timeframes longer than 25 years in the future. This question has been addressed in the literature previously. Bowerman et al. (2013) in particular show that reduction of SLCFs may have little impact on peak temperatures until the point at which peak CO_2 emissions have been passed. Bowerman also find that waiting until peak CO_2 emissions is the optimal time to reduce SLCF emissions in order to reduce the peak rate of warming. Rogelj et al. (2015) similarly find that delayed stringent mitigation of SLCFs is almost as good as immediate stringent mitigation in terms of peak warming and stabilization.

Perhaps part of the attraction of a short timescale is a function of the use of CO_2 as a reference gas. Consider a hypothetical scenario in which methane was used as a reference gas with a GWP of 100, and using a 100-year timescale, CO_2 had a GWP of 3.6. In this scenario, arguing for a 20-year timescale would be arguing for the CO_2 GWP to drop from 3.6 to

1.2. While mathematically equivalent to arguing for an increase in the CH4 GWP from 28 to 84, this framing would make it more clear that use of a short timescale leads to less emphasis on CO_2 mitigation, resulting in long term temperature increases.

S2. Expanded discussion of discounting

In the analysis presented in the main text, we restrict ourselves to applications of single discount rates. As noted in the text, this is applicable to US and other countries' policies but not to all nations. France and the UK, for example, have both endorsed the use of declining discount rates when valuing climate damages: as time progresses, the discount rate drops thereby leading to increased valuation of actions with long-term benefits such as reductions of CO_2 emissions. Though the UK uses a step-wise declining discount rate and France uses a continuous curve, both nations' discount rate paths average lower than the US' 3% and 7%. A number of researchers suggest that lower discount rates are most applicable for climate change. However, it is important to note that there is little consensus in the economics community as to what discount rate is appropriate and why or how it should be applied. For example, the UK's Stern Report (Stern, 2007) discount rate (which averages to 1.4%) has been subject to intense debate with economists concluding that the Stern discount is too low (Nordhaus, 2007), or is correct but not necessarily for the reasons stated in the review (Weitzman, 2007; Helm, 2008). As discussed in the main text, no stance is taken on the "correct" discount rate, nor have we yet evaluated the effects of a declining discount rate on the presented analysis. The effects of a declining discount rate on the discounted damages calculation would depend on the shape and timescale of the discounting. For a straightforward declining discount rate, an equivalent GWP timescale somewhere between the equivalent timescale of the starting discount rate and the ending discount rate would be expected. In the case where the declining discount rate was a byproduct of the use of the Ramsey framework with uncertain future growth rates, then it is less clear what the net effect on equivalent timescales would be.

S3. Expanded discussion of non-methane gases.

The main text includes a short discussion on gases other than CH_4 and CO_2, which is expanded here. In particular, as the 3rd most important well-mixed GHG (by standard metrics), we show an analysis of N_2O impacts. However, similar results would be found for any GHG with a century-scale lifetime, just as similar results to the CH_4 analysis apply for any GHG with a decadal lifetime.

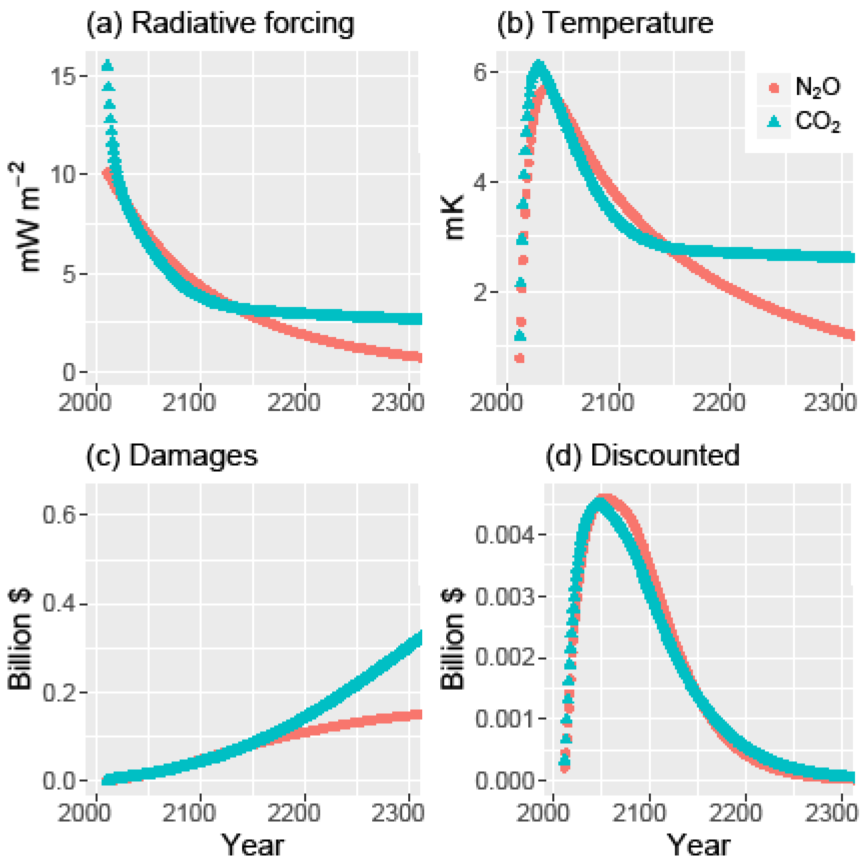

Figure S1: The impact of an emission pulse of N2O compared to an emission pulse of 312 times as much CO2 (the CO2 quantity being chosen to make the integrated damages at a 3% discount rate equivalent). Radiative forcing (a), Temperature(b), damages (c), and discounted damages (3%, d). The underlying scenario is RCP6.0, with other parameters at their central values.

Figure S1 is the equivalent figure to Fig. 1 of the main text, but for N_2O. For all 4 outcomes (radiative forcing, temperature, damages, and discounted damages) the impact of an emission pulse of CO_2 is similar to the impact of an emission pulse of N_2O. After that time, the long lifetime of CO_2 causes the CO_2 function to diverge from the N_2O functions, except in the case where discounting erases the damages. The similarity of these functions means that the relative radiative forcing and damages of N_2O to CO_2 are less sensitive to timescale and discount rate than for shorter lived gases.

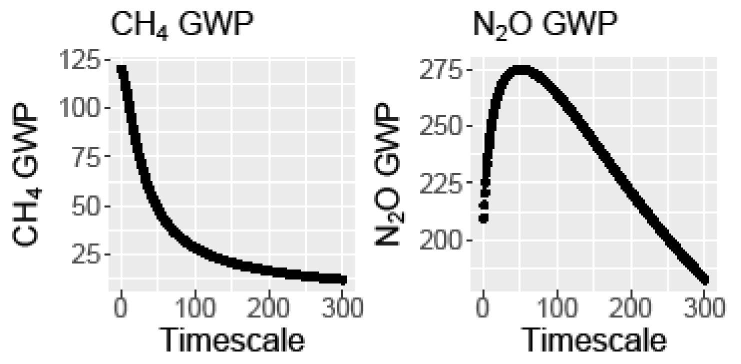

Figure S2: GWP as a function of time horizon for N_2O and CH_4.

An examination of the GWP as a function of timescale demonstrates the difference in the sensitivity of the N_2O GWP to timescale compared to sensitivity of the CH_4 GWP (see Fig. 2). As can be seen in the figure, the 1 year GWP is basically the ratio of instantaneous radiative forcing per ton of the emitted gas relative to CO_2. For methane, as the timescale increases, the GWP decreases monotonically due to the short lifetime. The N_2O function, however, is not monotonic. This is a result of the lifetime of CO_2 being determined by the sum of 4 exponentials, where two of those exponentials, accounting for more than 50% of the CO_2, have lifetimes substantially shorter than the N_2O lifetime, and the other 2 lifetimes being substantially longer. Therefore, as seen in Fig. S1(a), the radiative forcing of CO_2 decreases more quickly than that of N_2O for several decades, but then the rate of decrease in the radiative forcing of CO_2 slows as the short-lifetime pool of CO_2 is depleted. Because the GWP of N_2O never exceeds 275, it is not possible for a GWP timescale to be chosen for N_2O that can emulate a damage ratio of greater than 275 (as is the case at a discount rate of 3%, when the damage ratio is 312).

While the fact that one graph is monotonic and the other is not is the most striking difference between the CH_4 GWP graph and the N_2O GWP graph, there is another important difference which is the total variability. For CH_4, the difference between the instantaneous timescale and the 200-year timescale is a factor of 7. For N_2O, the difference between the peak GWP of 275 at a 52-year timescale, and either the instantaneous or the 200-year timescale, is less than 35%. That means that getting the timescale wrong for long-lived gases has a limited effect, whereas getting the timescale wrong for methane has substantial implications for the implied relative damages.

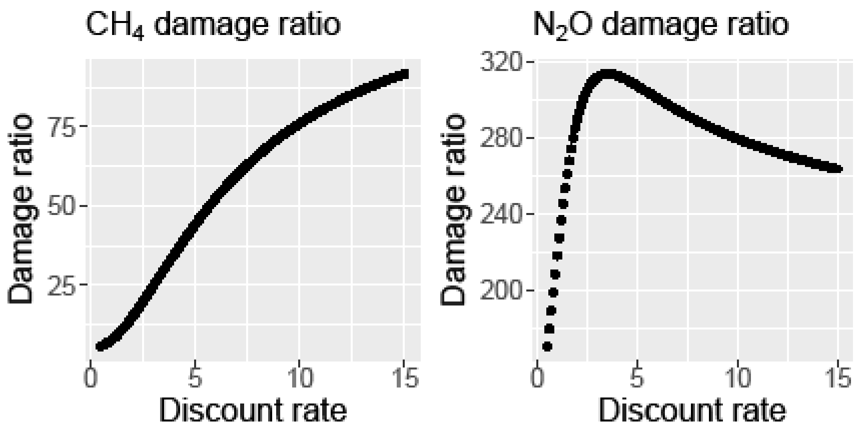

Figure S3: Using the central set of parameters, the ratio of the integrated discounted N2O (or CH4) damages to CO2 damages is calculated at each discount rate.

The relative damages for N_2O and CH_4 are shown in Fig. S3. Because of the non-monotonicity of the GWP graph for N_2O, showing a damage ratio graph is more straightforward than showing an implied timescale graph. Like the N_2O GWP graph, the damage ratio graph is also non-monotonic. Where it exceeds 275, there is no exact equivalent GWP timescale. At damage ratios below 275, there are two potential equivalent timescales, one less than 52 years and one greater than 52 years: alternatively, for an equivalent timescale, there are two potential matching discount rates. For example, for a GWP timescale of 100, the ratio of N_2O damages to CO_2 damages is 264, and discount rates of 1.6% and 14.9% both produce a damage ratio of 264.

The CH_4 damage ratio graph is also shown here. When convoluted with the GWP timescale graph, it produces the median line from Fig. 2 in the main text (see Fig. S4). We see that as the discount rate approaches infinity, the damage ratio approaches the instantaneous GWP. Unlike the N_2O damage graph, the CH_4 damage graph is monotonic with discount rate.

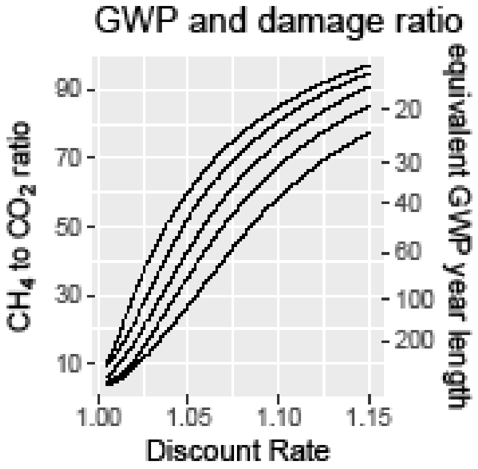

Figure S4: This shows the same data as in Fig. 2 in the main text. However, this figure is keyed to the damage ratio on the left axis, and the implied GWP timescale is shown on the right axis. Interdecile, interquartile, and median estimates are shown here as based on the sensitivity analysis.

This analysis suggests that the use of the implied timescale from the CH_4 results for all gases is a reasonable choice. First, because CH_4 is the most important non-CO_2 gas, but also because the implied timescale and damage ratios derived from the relative impacts of short-lived gases are much more sensitive to discount rates than the implied timescales and damage ratios for longer-lived gases.

Supplementary Information References

Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., & Forster, P. M.: New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Climate Change, 6(8), 773-776, 2016.

Bowerman, N. H., Frame, D. J., Huntingford, C., Lowe, J. A., Smith, S. M., & Allen, M. R.: The role of short-lived climate pollutants in meeting temperature goals. Nature Climate Change, 3(12), 1021 (2013).

Brazil's Intended Nationally Determined Contribution (Federative Republic of Brazil); available at http://www4.unfccc.int/submissions/INDC, 2015

Daniel, J. S., Solomon, S., Sanford, T. J., McFarland, M., Fuglestvedt, J. S., & Friedlingstein, P.: Limitations of single-basket trading: lessons from the Montreal Protocol for climate policy. Climatic Change, 111(2), 241-248, 2012.

De Cara, S., Debove, E., & Jayet, P. A.: Global Warming Potentials: Imperfect but second-best metric for climate change. Unpublished, available at http://stephane.decara.free.fr/mypdf/DeboDeCaJaye05b.pdf, 2005.

Fuglestvedt, J. S., Berntsen, T. K., Godal, O., Sausen, R., Shine, K. P., & Skodvin, T.: Metrics of climate change: Assessing radiative forcing and emission indices. Climatic Change, 58(3), 267-331, 2003.

Jackson, S. C.: Parallel pursuit of near-term and long-term climate mitigation. Science, 326(5952), 526-527, 2009.

Johansson, D. J.: Economics-and physical-based metrics for comparing greenhouse gases. Climatic Change, 110(1), 123-141, 2012.

Jørgensen, S. V., Hauschild, M. Z., & Nielsen, P. H.: Assessment of urgent impacts of greenhouse gas emissions—the climate tipping potential (CTP). The International Journal of Life Cycle Assessment, 19(4), 919-930, 2014.

Manne, A. S. & Richels, R. G.: An alternative approach to establishing trade-offs among greenhouse gases. Nature 410, 675–677, 2001.

Marten, A.L. & Newbold, S.C.: Estimating the social cost of non-CO2 GHG emissions: Methane and nitrous oxide. Energy Policy 51, 957-972, 2012.

Rogelj, J., Meinshausen, M., Schaeffer, M., Knutti, R., & Riahi, K.: Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. Environmental Research Letters, 10(7), 075001, 2015.

Sarofim, M., Forest, C., Reiner, D., Reilly, J.: Stabilization and global climate change. Glob Planet Change 47:266–272, 2005.

Shindell, D. T., Fuglestvedt, J. S., & Collins, W. J.: The social cost of methane: theory and applications. Faraday Discussions, 2017.

Shine, K., Fuglestvedt, J., Hailemariam, K. & Stuber, N.: Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. Climatic Change 68, 281–302, 2005.

Smith, S. M., Lowe, J. A., Bowerman, N. H. A., Gohar, L. K., Huntingford, C., and Allen, M. R.: Equivalence of greenhouse gas emissions for peak temperature limits, Nature Climate Change, 2(7), 535–538, doi:10.1038/NCLIMATE1496, 2012.

Tanaka, K., Johansson, D. J., O'Neill, B. C., & Fuglestvedt, J. S.: Emission metrics under the 2 C climate stabilization target. Climatic Change, 117(4), 933-941, 2013.

Zickfeld, K., Eby, M., Matthews, H. D., & Weaver, A. J.: Setting cumulative emissions targets to reduce the risk of dangerous climate change. Proceedings of the National Academy of Sciences, 106(38), 16129-16134, 2009.