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The Marginal Damage Costs of Different Greenhouse Gases: An Application of FUND

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Abstract
The authors use FUND 3.9 to estimate the social cost of four greenhouse gases—carbon dioxide, methane, nitrous oxide, and sulphur hexafluoride—with sensitivity tests for carbon dioxide fertilization, terrestrial feedbacks, climate sensitivity, discounting, equity weighting, and socioeconomic and emissions assumptions. They also estimate the global damage potential for each gas—the ratio of the social cost of the non-carbon dioxide greenhouse gas to the social cost of carbon dioxide. For all gases, they find the social costs and damage potentials sensitive to alternative assumptions. The global damage potentials are compared to global warming potentials (GWPs), a key metric used to compare gases. The authors find that global damage potentials are higher than GWPs in nearly all sensitivities. This finding suggests that previous papers using GWPs may be underestimating the relative importance of reducing non-carbon dioxide greenhouse gas emissions from a climate damage perspective. Of particular interest is the sensitivity of results to carbon dioxide fertilization, which notably reduces the social cost of carbon dioxide, but only has a small effect on the other gases. As a result, the global damage potentials for methane and nitrous oxide are much higher with carbon dioxide fertilization included, and higher than many previous estimates.

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Keywords Climate change; social cost; carbon dioxide; methane; nitrous oxide; sulphur hexafluoride

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1 Introduction

Climate change is affected by the emissions of many greenhouse gases (GHGs). Carbon dioxide (CO_2) is the primary GHG and the majority of research on the benefits of mitigation has focused on CO_2. However, in order to create effective and least cost climate policies, reductions in the emissions of all greenhouse gases should be considered (Weyant et al. 2006). This necessitates a mechanism to weigh the potential trade-offs between the various greenhouse gases.

There are a number of methods for comparing different greenhouse gases (Tol et al. 2012). The most common approach is a physical measure, such as the Global Warming Potentials (GWP) and Global Temperature change Potential (GTP)[1] (Myhre et al. 2013; Forster et al. 2007). However, this is essentially arbitrary from an economic, decision analytic perspective because it does not weigh the potential differences in welfare effects across gases.[2] Another approach is that of Manne and Richels (2001), who examine the ratio of the shadow prices of non-CO_2 GHGs to CO_2 in GHG mitigation scenarios. This is appropriate when seeking to meet a specific temperature, concentration, or emissions target at the lowest possible cost. Embedded within such calculations are marginal trade-offs between gases in terms of their impacts. Finally, as is done in this paper, the ratio of marginal impacts of each non-CO_2 GHG to CO_2 reflects the relative value of GHGs in terms of climate change damages. This metric should be used if one seeks to account for damages from globally incremental changes in all GHGs.

The importance of estimating appropriate trade-offs between greenhouse gases in a cost-benefit framework was recognized in the early 1990s (Eckaus 1992; Michaelis 1992; Schmalensee 1993). Shortly thereafter, a number of papers sought to quantify the ratios of the relative marginal damage of greenhouse gas *i* with respect to the marginal damage of CO_2, then dubbed the "global damage potential" (Fankhauser 1995; Hammitt et al. 1996; Kandlikar 1995; Kandlikar 1996; Reilly

[1] The GWP is defined as the integral of the radiative forcing from the emission of 1 kg of an individual GHG divided by the integral of the radiate forcing for 1 kg CO_2 emissions, over a specified period (e.g. 20 or 100 years). The GTP is defined as the ratio of the global mean surface temperature change, after a specific period of time, due a unit emission of a GHG compared to the change from a unit emission of CO_2.

[2] Because different greenhouse gases have different atmospheric lifetimes, the discounted value of future damages will vary.

and Richards 1993; Wallis and Lucas 1994). Since then, relatively little research (Hope 2006; Tol 1999; Marten and Newbold 2012) has been focused on this issue, even though our understanding of the impacts of climate change has improved (Tol 2009b). We therefore revisit the damage potential of methane, nitrous oxide, and sulphur hexafluoride emissions, offering new estimates using the FUND model.

An additional motivation for this paper is that policy-makers have begun to value changes in greenhouse gas emissions in regulatory decisions (Rose 2012). This has led to new interest in how to value the relative impacts of different gases. However, with the legal focus on CO_2 emissions and a dearth of non-CO_2 GHG emission reduction benefit estimates, decision-makers have opted to use either CO_2 marginal value estimates with emissions converted to CO_2 equivalents based on global warming potentials (DEFRA 2007; EPA 2012) or not value changes in non-CO_2 GHG emissions at all (USDoE 2010). This paper helps inform this issue by providing direct estimates of both the social costs of each GHG and non-CO_2 GHG damage potentials.

Finally, this paper examines the sensitivity of our estimates to an array of parameters. Estimates are sensitive to many assumptions and focuses on the effects of six parameters: carbon dioxide fertilization in agriculture, terrestrial feedbacks, climate sensitivity, discounting, equity weighting, and socio-economic and emissions scenarios.

The paper continues as follows: Section 2 presents the model, Section 3 discusses the results, and Section 4 concludes. There are two companion papers, one focusing on the social cost of carbon per sector and region (Anthoff et al. 2011a), and one focusing on the evolution of the social cost of carbon over time (Anthoff et al. 2011b).

2 The Model

The results in this paper are generated with version 3.9 of the *Climate Framework for Uncertainty,* Negotiation *and Distribution* (*FUND*).[3] FUND is an integrated

[3] Version 3.9 of FUND corresponds to version 3.8 except that SO2 radiative forcing is specified exogenously. A full list of papers, the source code, and the technical documentation for the model can be found on line at http://www.fund-model.org/.

assessment model with simplified representations of development, energy use, carbon cycle, and climate. The model has been used to study cost-effective, efficient, feasible and equitable climate policy. It differs from other integrated assessment models in its more detailed representation of the sectoral and regional economic impacts of climate change.

The model distinguishes 16 major regions of the world: the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 3000 in one year time steps. The model starts in 1950 to initialize the climate change impact module.[4] Previous versions of the model stopped at 2300, but a longer time horizon is needed if low discount rates are used. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, thereby capturing adaptation to climate change.

Each scenario is defined initially by exogenous assumptions about the rates of population growth, economic growth, autonomous energy efficiency improvements, and the rate of decarbonization of energy use (autonomous carbon efficiency improvements), which together result in emissions of carbon dioxide from fossil fuel use and land use change and emissions of methane, nitrous oxide, sulphur hexafluoride and aerosols. The scenarios of economic and population growth are perturbed by the impacts of climatic change. For instance, population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and storms. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org).

[4] Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The period of 1950–2000 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk 1994). The scenario for the period 2010–2100 is based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). The base scenario is for illustrative purposes only; a sensitivity analysis on scenario assumptions is included in this paper. The 2000–2010 period is interpolated from the immediate past (http://earthtrends.wri.org), and the period 2100–3000 extrapolated.

It is extrapolated based on the statistical relationship between urbanization and per capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change.

FUND derives atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, from which radiative forcing, global mean temperature, and sea level rise are computed. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. For FUND version 3.8, the atmospheric lifetime parameters for N_2O and CH_4 concentrations were updated to 114 and 12 years respectively (from Table 2.14 in Forster et al. 2007). The change in atmospheric concentration of carbon dioxide in response to emissions, measured in parts per million by volume, is represented by a linear impulse response function (Hammitt et al. 1992; Maier-Reimer and Hasselmann 1987). Feedback effects from climate on the amount of CO_2 that is stored and emitted by the terrestrial biosphere is modelled as in (Tol 2009a).[5]

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride is as in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (Forster et al. 2007). In FUND 3.8, radiative forcing for CH_4 was changed to include indirect effects of methane on tropospheric ozone (Forster et al. 2007), but not its effect on sulphate aerosols (Shindell et al. 2009). Table 1 shows the global warming potentials as computed by the *FUND* climate model. The global mean temperature *T* is governed by a geometric build-up to its equilibrium (determined by the radiative forcing *RF*), with a calibrated e-folding time that depends on the climate sensitivity (for the base climate sensitivity of 3.0 the e-folding time is 44 years). In the base scenario, the global mean temperature rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents. Regional temperatures follow from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al. 2000). The dynamics of the global mean sea level are also geometric, with its equilibrium level determined by the temperature and a calibrated e-folding time of 500 years. Both temperature and sea level are calibrated to correspond to the best

[5] Potential feedback between the climate and the ocean carbon sink is not modeled.

Table 1: Global Warming Potentials as computed by FUND

Years	CH_4	N_2O	SF_6
20	74	449	15,623
100	29	564	28,052
500	11	382	61,049
AR4 - 100	25	298	22,800
AR5 - 100	28	265	23,500

The dynamic biosphere was switched off for these calculations. The IPCC AR4 and AR5 100-year GWPs are from Forster et al. (2007) and Myhre et al. (2013), respectively.

guess temperature and sea level for the IS92a scenario (Kattenberg et al. 1996). Note that we are here interested in the *marginal* impacts, which are primarily driven by the *response* of climate and temperature to a *change* in emissions.

The climate impact module includes the following impact categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, energy consumption, water resources, unmanaged ecosystems (Tol 2002a; Tol 2002b), diarrhoea (Link and Tol 2004), and tropical and extra tropical storms (Narita et al. 2009; Narita et al. 2010). Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (Tol 2002b). Impact functions are calibrated to the results of economic impact models reported in the literature. Occasionally, adjustments are made; for instance, computable general equilibrium models of the impact of climate change on agriculture make overly optimistic assumption about the effects of carbon dioxide fertilization (Long et al. 2006), and have been adjusted downwards.

Climate change affects population growth through premature deaths or migration due to sea level rise. Like all the impacts of climate change in FUND, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income.[6] The resulting value of a statistical life lies in the middle of the observed range of values in the literature (Cline 1992). The value of

[6] See (Cropper et al. 2011) for a review of recent empirical studies of the value of a statistical life.

emigration is set to be 3 times the per capita income (Tol 1995), the value of immigration is 40 per cent of the per capita income in the host region (Cline 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (Fankhauser 1994a). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (Fankhauser 1994a). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, storm damage, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (Tol 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (Tol 2002b).

The impacts of climate change on coastal zones, forestry, tropical and extratropical storms, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (Tol 2002b).

Climate change vulnerability changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable over time with increasing climate change, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) are projected to become less vulnerable at least over the long term (Tol 2002b).

We estimate the social cost[7] of a greenhouse gas by first computing the difference between total, monetised climate change impacts of a business as usual emissions and socio-economic path and a path with slightly higher emissions between 2010 and 2019.[8] The differences in monetized climate change impacts are discounted back to the current year (2010), and normalised by the difference in emissions.[9] The social cost measures of the additional impacts globally of an additional global tonne of emissions, which we express in 1995 dollars per tonne of greenhouse gas in 2010. It is also used as a measure of how much future damage would be avoided if today's emissions were reduced by one tonne. The social cost of any greenhouse gas is computed as follows:

$$SC_{r,i} = \sum_{t=2010}^{3000} \frac{D_{t,r}(E_{1950}+\delta_{1950},\dots,E_t+\delta_t) - D_{t,r}(E_{1950},\dots,E_t)}{\prod_{s=2010}^{t} 1+\rho+\eta g_{s,r}} \Bigg/ \sum_{t=1950}^{3000} \delta_t \tag{1}$$

$$\delta_t = \begin{cases} \omega & \text{for } 2010 \le t < 2020 \\ 0 & \text{for all other cases} \end{cases}$$

where

- $SC_{r,i}$ is the regional social cost of greenhouse gas i (in 1995 US dollars per tonne of i);
- r denotes region;
- i denotes greenhouse gas;
- t and s denote time (in years);
- D are monetised impacts (in 1995 US dollars per year);

[7] The social cost of a greenhouse gas is defined as the net present value of the change in future damages from a marginal (1 tonne) change in emissions of that gas today.

[8] The social cost of emissions in future or past periods is beyond the scope of this paper.

[9] We abstained from levelizing the incremental impacts within the period 2010–2019 because the numerical effect of this correction is minimal.

– E are emissions of greenhouse gas i (in metric tonnes of i per year);
– δ are incremental emissions (in metric tonnes of i per year);
– ω are increment emissions (in metric tonnes of i per year);
– ρ is the pure rate of time preference (in fraction per year);
– η is the elasticity of marginal utility with respect to consumption; and
– g is the growth rate of per capita consumption (in fraction per year).

We first compute the SC_i per region, and then aggregate, as follows

$$SC_i = \sum_{r=1}^{16} \left(\frac{Y_{2010,ref}}{Y_{2010,r}} \right)^{\epsilon} SC_{r,i} \tag{2}$$

where

– SC_i is the global social cost of greenhouse gas i (in 1995 US dollars per tonne of i);
– $Y_{2010,ref}$ is the average per capita consumption in the reference region in 2010 (in US dollars per person per year); the reference region may be the world (Fankhauser et al. 1997) or one of the regions (Anthoff et al. 2009);
– $Y_{2010,r}$ is the regional average per capita consumption in 2010 (in 1995 US dollars per person per year); and
– ε is the rate of inequity aversion; $\varepsilon = 0$ in the case without equity weighing; $\varepsilon = \eta$ in the case with equity weighing.

The unitless damage potential of greenhouse gas i, i.e., the relative marginal damage of greenhouse gas i with respect to the social cost of carbon dioxide, is defined as

$$DP_i = \frac{SC_i}{SC_{CO2}} \tag{3}$$

where

– DP_i is the damage potential of greenhouse gas *i* (unitless).

Because non-CO_2 GHGs do not have fertilization effects like CO_2, it is useful to decompose the social cost of carbon dioxide denominator into its effect on climate change and its fertilization effect:

$$DP_i = \frac{SC_i}{SC_{CO2}} =: \frac{SC_i}{SC_{CO2}^{CC} + SC_{CO2}^{fert}} =: \frac{f_i(\vartheta, \varphi)}{f_{CO2}(\vartheta, \varphi) + g_{CO2}(\vartheta, \psi)} \tag{4}$$

Equation (4) is an expansion of Equation (3), highlighting that the social cost of carbon dioxide effects on climate change and the social cost of other greenhouse gases are functions of the same vector of parameters. The social cost of carbon dioxide fertilization effects on crop yields is a different function, although with some overlapping parameters. This implies that, without carbon dioxide fertilization, one would expect the damage potential of greenhouse gas *i* with respect to the social cost of carbon dioxide potential to be largely robust to parameter variations. Conversely, with carbon dioxide fertilization, one would not expect that to be the case.

3 Results and Sensitivities

3.1 Social Cost of Carbon Dioxide

Figure 1 shows our estimates for the social costs of carbon dioxide (SC-CO_2). The base case estimate is \$6.6/t-CO_2.[10,11] A large number of assumptions are needed to produce this estimate and we examine the sensitivity of this estimate with respect to carbon dioxide fertilization, tropical forest dieback, climate sensitivity, pure rate

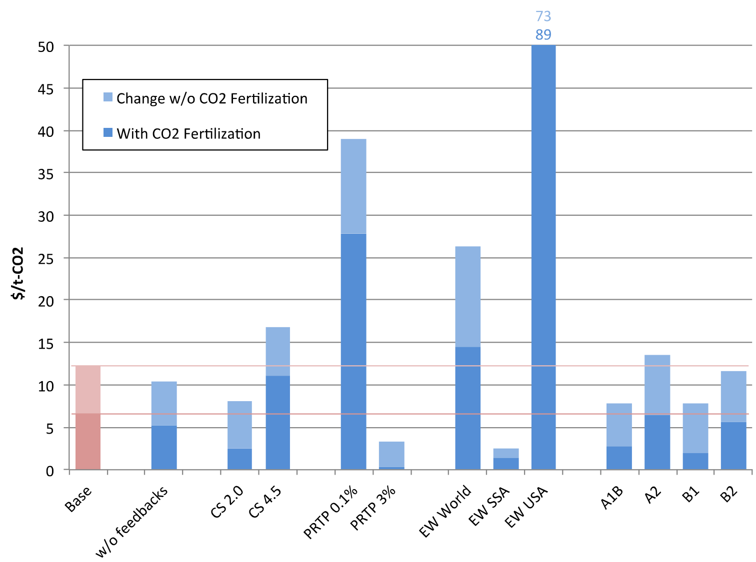
10 As noted in Section 2, all results presented here are in 1995\$. Adjusting for inflation to 2007\$ (multiplying by 1.38) would increase our base estimate of the SC-CO_2 to roughly \$9.1.

11 This compares with the official US Government SCC values that range from 11-89 2007\$/t-CO_2, with a central estimate of 32 2007\$/t-CO_2 in 2010. http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf

of time preference, equity weights, and socio-economic and emissions scenarios. These are all considered individually as single deviations from the base case. The base case includes carbon dioxide fertilization, tropical forest drying, climate sensitivity of three, pure rate of time preference of 1%, no equity weighting, and the FUND default socioeconomic and emissions scenario.

The positive effects of carbon dioxide fertilization on agriculture partially offset negative climate change impacts. If the carbon dioxide fertilization effect is removed,[12] the SC-CO_2 rises to \$12/t-CO_2. The effect of carbon dioxide fertilization is comparatively large because it occurs in the near future, thus having a relatively larger effect on the net present value of future damages than the

Figure 1: Estimates of the social cost of carbon dioxide emissions in 2010 (1995\$)



Red denotes the estimate with the base assumptions for each parameter. Darker colours include carbon dioxide fertilization, the sum of the dark and light are estimates without carbon dioxide fertilization. Note that the values for EW USA exceed the scale of the chart. The bottom number is the value with CO_2 fertilization and the sum of the two values is the value without CO_2 fertilization.

[12] Note that we only consider the direct effects of carbon dioxide fertilization on the impacts of climate change on agriculture in this sensitivity analysis.

negative impacts that occur in later time periods. The sensitivity of the estimate to other parameters shows a wide range of outcomes, both large and small, positive and negative.

The dieback of tropical forests and the resulting release of substantial CO_2 emissions because of climate change increases the SC-CO_2 estimate. Without this feedback, the SC-CO_2 falls to \$5.2/t-CO_2. This effect is relatively small when compared with carbon dioxide fertilization because it occurs in the more distant future and is thus discounted more heavily.

Climate sensitivity, or the equilibrium warming due to a doubling of carbon dioxide concentrations, has a larger effect on the SC-CO_2 estimates than either tropical forest feedbacks or CO_2 fertilization. Our base case estimate assumes a climate sensitivity of 3.0°C.[13] Using a climate sensitivity of 2.0°C or 4.5°C causes the SC-CO_2 to fall to \$2.5/t-CO_2 or rise to \$11/t-CO_2, respectively. The higher the climate sensitivity, the greater the temperature response to a given level of emissions and the larger the resulting damages.

Because of the long-term nature of climate change impacts and the amount of time CO_2 remains in the atmosphere, the net present value of all future damages is greatly affected by the rate at which those damages are discounted. Our sensitivity analyses with respect to the discount rate have a very large affect on the SC-CO_2 estimate. In our base case, the pure rate of time preference is 1% per year, implying a discount rate of roughly 3% per year, on average.[14] A pure rate of time preference of 0.1% or 3% per year causes the social cost of carbon dioxide to rise to \$28/t-CO_2 or fall to only \$0.3/t-CO_2, respectively.

The base case assumptions do not include equity weights. Equity weighting increases the relative weight of the damages that occur in poorer regions. For recent discussions on equity weights, see (Anthoff et al. 2009; Anthoff and Tol 2010; Rose 2012). With large variation in regional GDP per capita, SC-CO_2 estimates are very responsive to equity weighting (Anthoff et al. 2009). If world-average equity weights are used, the social cost rises to \$14/t-CO_2. If instead, U.S.

[13] This is the modal estimate of climate sensitivity (Randall et al. 2007).

[14] The discount rate is implemented in the model through the Ramsey equation: the discount rate (r) is calculated by $r = \rho + \eta g$, where ρ = pure rate of time preference, η is the marginal utility of consumption, and g is the annual growth rate of regional GDP. In the FUND base case $\eta = 1$ and $g \approx 2\%$ (on average), but varies by region and year. So, with $\rho = 1\%$, $r \approx 3\%$.

or sub-Saharan African equity weights are used, the social cost estimates are \$89/t-CO_2 and \$1.4/t-CO_2, respectively.

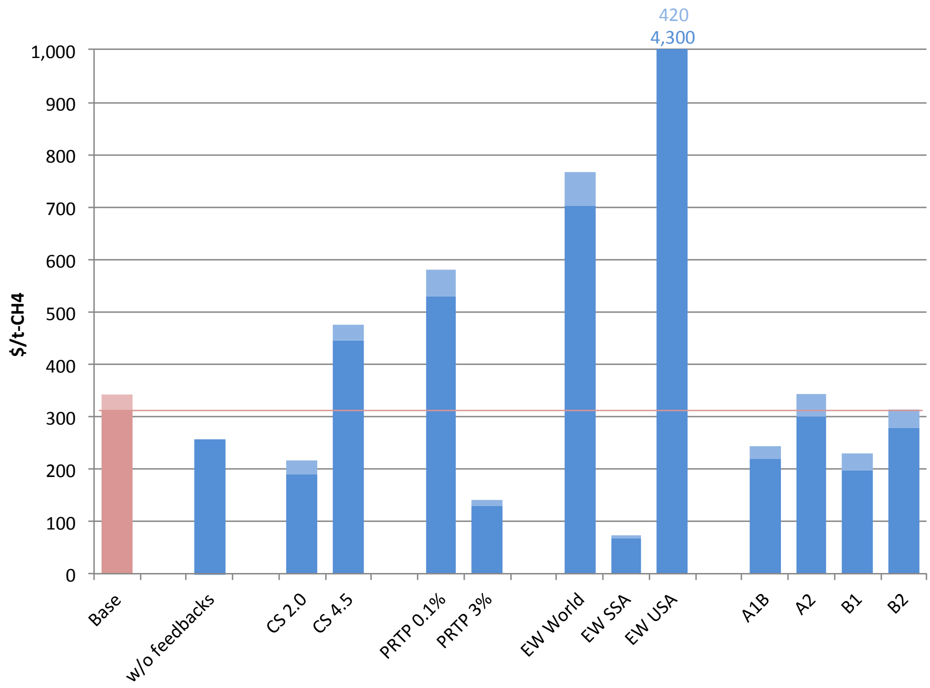
Finally, estimates are sensitive to assumptions about future economic, population, and emissions scenarios. The base case estimate uses population, income, and emissions according to the FUND scenario as described in Section 2. To test the sensitivity of these results to scenario assumptions, estimates are also generated using the range of SRES scenarios (Nakicenovic and Swart 2001). Under the B1 scenario, which is a low emissions/low growth scenario, the SC-CO_2 is \$2.0/t-CO_2. The A1B scenario, which assumes a high emissions/low growth world, the estimate is \$2.7/t-CO_2. With a B2 scenario, a low emissions/high growth world, the SC-CO_2 is \$5.6/t-CO_2. Finally, under the high emissions/high growth world of the A2 scenario, the SC-CO_2 is \$6.5/t-CO_2. The alternate scenarios make clear that the social cost of carbon dioxide depends not only on the level of emissions and climate change, but also on the vulnerability of society to climate change and the valuation of impacts, both of which are driven by economic development.

An important caveat to these estimates is that FUND does not currently estimate the potential additional damages from ocean acidification due to an incremental tonne of CO_2. While CO_2 fertilization lowers the net damage, ocean acidification could raise the net damages.

3.2 Social Cost of Methane

The social costs of methane emissions are shown in Figure 2. As with SC-CO_2, the sensitivity of SC-CH_4 is estimated with respect to a number of assumptions. In the base case, the estimate is \$313/t-CH_4. As expected, the qualitative pattern of changes in the SC-CH_4 across sensitivities to these assumptions is the same as in Figure 1. The impacts of climate change respond in the same direction to parameter variations regardless of whether additional climate change is caused by methane or carbon dioxide. The primary differences are related to the differences in the time profile of warming between the gases. Additionally, compared to our estimate with carbon dioxide fertilization, there is a small increase in SC-CH_4 because of the lack of positive effects of CO_2 fertilization on agricultural yields. Therefore economic growth will be slightly lower, causing populations to be a bit more vulnerable to climate change.

Figure 2: Estimates of the social costs of methane emissions in 2010 (1995$)



Red denotes the base assumptions. Darker colours include carbon dioxide fertilization, the sum of the dark and light are estimates without carbon dioxide fertilization. Note that the values for EW USA exceed the scale of the chart. The bottom number is the value with CO_2 fertilization and the sum of the two values is the value without CO_2 fertilization.

Figure 3 shows the methane damage potential, that is, the ratio of the social cost of methane to the social cost of carbon dioxide. In the base case (top panel), the estimated damage from emitting an additional tonne of methane is 48 times more than the damage from emitting an additional tonne of carbon dioxide.[15] As

[15] As noted above, the effects of CO2 on ocean acidification would increase the SC-CO2. Ocean acidification is not affected by CH4, N2O, or SF6 emissions and its inclusion would not affect the SC estimates for these gases. Therefore the inclusion of ocean acidification damages would tend to lower the damage potential of each of the non-CO2 GHGs, as only the denominator in the ratio would increase.

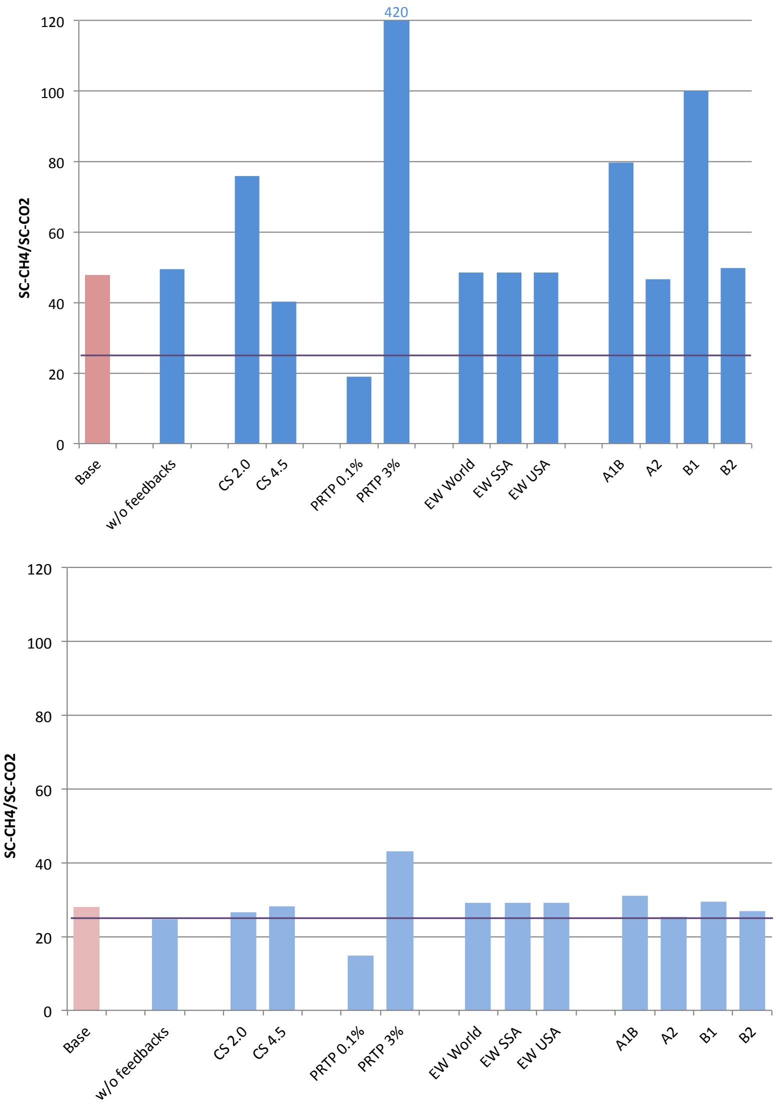
seen in the top panel of Figure 3, the CH_4 damage potential remains largely unchanged for sensitivities to the terrestrial carbon cycle and equity weighting, though it varies with the other assumptions described above. The IPCC 100-year global warming potential (GWP) estimates in the Fifth Assessment Report (AR5) and Fourth Assessment Report are 28 and 25, respectively (Myhre et al. 2013; Forster et al. 2007), while the official internationally negotiated United Nations Framework Convention on Climate Change (UNFCCC) estimate is 21 (Schimel et al. 1996). As noted above, the 100-year GWP computed by FUND is 29.1 (Table 1). The methane damage potential is greater than the AR4 100-year GWP of 25 in every sensitivity run except when the PRTP is 0.1%. This is because the lifetime of CH_4 is much shorter than CO_2 so there are proportionately lower impacts for CH_4 occurring far in the future and a very low discount rate gives a greater weight to the longer-term impacts caused by CO_2.

Assumptions about climate sensitivity have a large impact on the CH_4 damage potential. It falls to 40 when the climate sensitivity is 4.5°C and rises to 76 with a climate sensitivity of 2.0°C. This effect is largely due to the effect of carbon dioxide fertilization on the SC-CO_2—the denominator of the CH_4 damage potential. The absolute benefits from CO_2 fertilization are a relatively constant level value and therefore have a larger proportional effect on the SC-CO_2 under a low (2.0°C) climate sensitivity, while under a high (4.5°C) climate sensitivity, temperature-related damages from CO_2 are higher and the CO_2 fertilization benefits are therefore a smaller share of the overall SC-CO_2. Without CO_2 fertilization, the methane damage potential is roughly constant across all CS levels because these reflect only differences in the time profile of climate damages.

A similar, but larger, change due to the different time profiles of the damages from the gases is observed for variations in the pure rate of time preference. The CH_4 damage potential falls to 19 for a pure rate of time preference of 0.1% and rises to 422 when the pure rate of time preference is increased to 3.0%/yr. The longer atmospheric lifetime of CO_2 makes its social cost much more sensitive to the discount rate than that of CH_4. As the lower panel of Figure 3 shows, the near-term benefits of carbon dioxide fertilization also influence this result. Without it, the CH_4 damage potentials are 15 and 43 for PRTP of 0.1% and 3%, respectively.

The damage potential for equity-weighted damages is almost equal to the damage potential of the base case, namely 49 with CO_2 fertilization and 29 without

Figure 3: The global damage potential of methane in 2010 under multiple scenarios



The top panel shows ratios with carbon dioxide fertilization and the bottom panel shows them without carbon dioxide fertilization. The purple line shows the AR4 global warming potential (25).

CO_2 fertilization. The different equity weighting schemes all have exactly the same damage potential, as expected: the only difference between the three equity weighting schemes is the choice of $Y_{2010,ref}$ in equation (2), but given that this is the same choice for both the social cost of carbon and the social cost of some other gas, the differences between the three equity weighting schemes cancels out if one takes the ratio of the social cost of two different gases (as one does when computing the global damage potential).

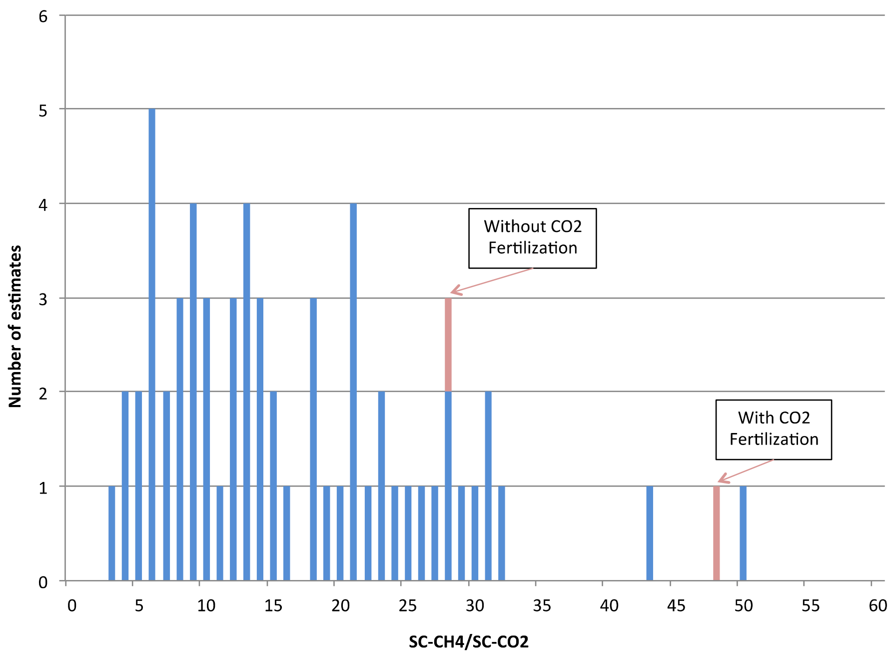
Socioeconomic and emissions scenarios tend to be more similar in the near term than in the longer term and therefore have a greater effect on longer lived gases and the social cost of carbon dioxide. The methane damage potential therefore varies considerably between scenarios, ranging between 47 and 100 for the A2 and B1 scenarios with CO_2 fertilization, respectively. As with many of the other sensitivities, carbon fertilization strengthens the differences for the reasons described above. In the B1 (and to a lesser extent A1B) scenario, the comparatively lower emissions and wealthier society increases the relative benefits from CO_2 fertilization, thus increasing the denominator by a factor of 3 while only increasing the numerator by ~15%. So although the absolute values of the CH_4 damages are highest in the high emitting worlds of A2 and B2, the relative impacts compared to CO_2 are highest in the lower emitting worlds and society is more sensitive to changes in methane emissions.

Without the positive benefits of CO_2 fertilization (Figure 3, bottom panel), the SC-CO_2 is much larger while the SC-CH_4 is only slightly larger. The result is that the base case damage potential falls to 28 from 48. Without CO_2 fertilization, the damage potential reflects only radiative forcing damages, so the remaining differences are due to the differences in atmospheric lifetime between the gases and the effect of discounting.[16] In the absence of CO_2 fertilization, the CH_4 damage potential is fairly constant across sensitivities, with the exception of the pure rate of time preference. This effect is quite profound given the wide range of CH_4 damage potentials with CO_2 fertilization. It emphasizes the interaction of CO_2 fertilization with the other sensitivity parameters. Without the effects of CO_2 fertilization, the other parameters impact damages for both gases with similar ratios.

[16] Social cost values are the sum of discounted future damages so are dependent on both the time profile of the damages and the discount rate, while the GWP is not discounted but rather truncated at a given horizon (in this case, 100 years).

Figure 4 shows our estimates of the damage potential of methane in comparison to earlier estimates (Fankhauser 1994b; Hammitt et al. 1996; Hope 2006; Kandlikar 1995; Kandlikar 1996; Reilly and Richards 1993; Tol 1999).[17] The 61 previous estimates are shown as a histogram in blue. Without CO_2 fertilization our primary estimate is 28, which falls on the upper end of the range

Figure 4: Histogram of our base estimate and our estimate without CO_2 fertilization of the damage potential of methane in 2010 (in red) compared to previous estimates



Note that the estimates from this paper are for perturbations in the year 2010, while the estimates from earlier literature represent perturbations in the year 1995 or earlier. Because the social costs of GHGs tend to grow over time, but may not change at identical rates, comparison with earlier estimates is illustrative only.

[17] The values shown in Figure 4 are estimates for multiple emissions years, most likely 1995 or earlier, while our estimates are for emissions in 2010. Because the social costs of GHGs tend to grow over time (Anthoff et al. 2011b) and may not change at an identical rate, the global damage potentials may also vary over time.

of previous estimates (from 3 to 50). This comparison is most appropriate because these earlier estimates, except for (Reilly and Richards 1993), do not include the effects of carbon dioxide fertilization. However, our primary estimate of the damage potential for methane is 49, which is greater than all but one of the previous estimates. This is not unexpected for two reasons. First, our base estimate includes CO_2 fertilization (decreasing the denominator) and second, the indirect radiative forcing effects from methane, which are approximately 40% greater than the direct effects alone, are included in our estimates of the SC-CH_4 (increasing the numerator).

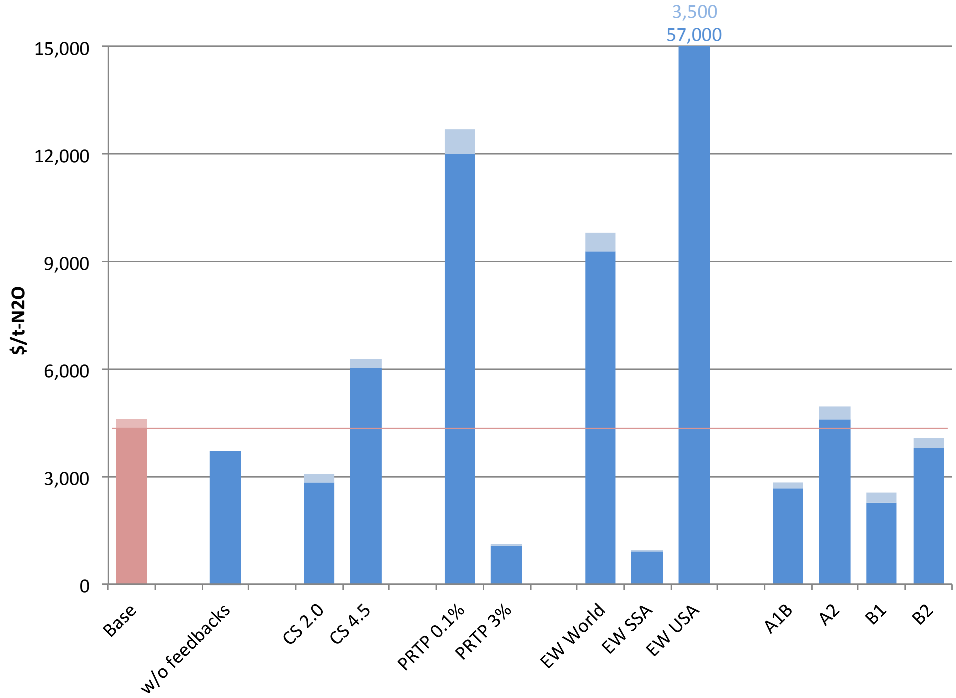
3.3 Social Cost of Nitrous Oxide

Figure 5 shows the social cost of nitrous oxide emissions. The estimate is \$4,360/t-N_2O using the base case assumptions. Qualitatively, the pattern is the same as for carbon dioxide and methane (Figures 1 and 2). However, because of the longer atmospheric lifetime for nitrous oxide, its social cost is more sensitive than the social cost of methane to the pure rate of time preference and the socioeconomic scenario, both of which have proportionately larger impacts in the long term. However, the effect on the social cost measure to changes in the climate sensitivity, which also has larger impacts in the long term, is very similar between N_2O and CH_4.

Figure 6 shows the nitrous oxide damage potential for our base assumptions and each sensitivity run. In the base case the net present value of the damage from a marginal tonne of nitrous oxide is 665 times more than for carbon dioxide. Without the effect of carbon dioxide fertilization, the estimate falls to 376. Our primary estimate is more than two times the IPCC 100-year global warming potential of 265 (AR5, Myhre et al. 2013), 298 (AR4, Forster et al. 2007), and the official UNFCCC value of 310 (Schimel et al. 1996).

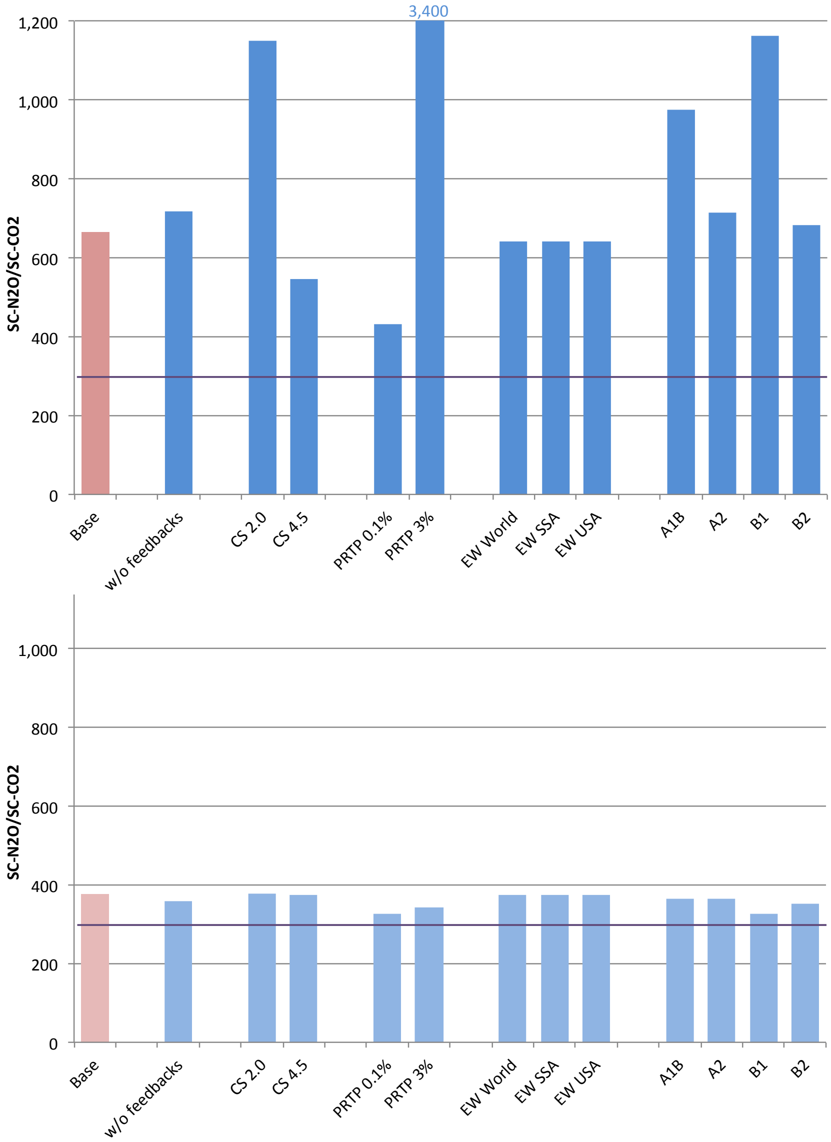
Eliminating the climate change feedback on the terrestrial carbon cycle causes the N_2O damage potential to rise slightly to 717. As with the pattern for methane, the nitrous oxide damage potential falls to 545 and rises to 1,149 as the climate sensitivity is changed to 4.5°C or 2.0°C, respectively. Again, this difference disappears without carbon dioxide fertilization, as the marginal impacts of nitrous oxide and carbon dioxide respond in the same way to the climate sensitivity because they both have comparatively long atmospheric lifetimes.

Figure 5: Estimates of the social cost of nitrous oxide emissions in 2010 (1995$)



Red denotes the estimate with our base assumptions. Darker colours include carbon dioxide fertilization, the sum of the dark and light are estimates without carbon dioxide fertilization. Note that the values for EW USA exceed the scale of the chart. The bottom number is the value with CO2 fertilization and the sum of the two values is the value without CO2 fertilization.

Figure 6: The damage potential of nitrous oxide in 2010 under multiple scenarios



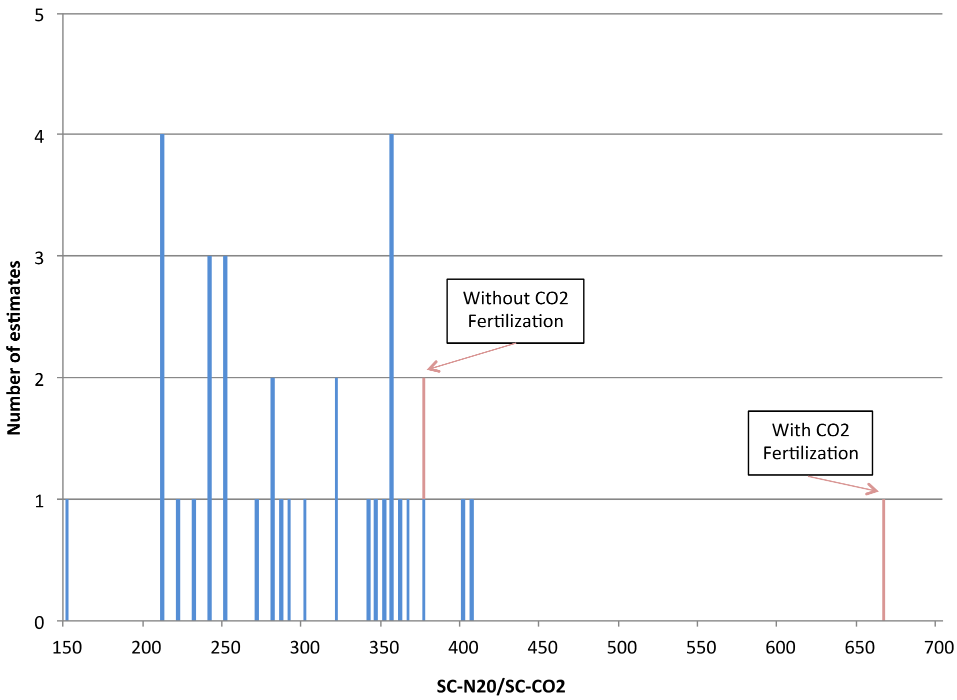
The top panel shows ratios with carbon dioxide fertilization and the bottom panel shows them without carbon dioxide fertilization. The purple line shows the AR4 global warming potential (298).

Changing the pure rate of time preference to 0.1%/yr and 3.0%/yr, while maintaining the other base case assumptions, causes the N_2O damage potential to fall to 433 and rise to 3,438 respectively. The N_2O damage potential is very high at a PRTP of 3% because the initial benefits of carbon dioxide fertilization are weighted more heavily compared to the longer-term damages of both gases, which are discounted heavily with the higher PRTP. When the benefits of carbon dioxide fertilization are not included, however, the damage potential is highest at a pure rate of time preference of 1%. This is because nitrous oxide has a constant rate of atmospheric removal, whereas carbon dioxide has a declining rate of removal. Thus, there is more carbon dioxide (relative to the initial pulse) than nitrous oxide in both the short run and the very long run.

As for the damage potential of CH_4, the N_2O damage potential is essentially unchanged with equity weighting, from a base estimate of 665 to 642 with equity weighting in any region. As expected, the N_2O damage potential varies across scenarios with CO_2 fertilization, ranging from 681 (B2) to 1,162 (B1). The magnitude of the differences across scenarios is not as large for N_2O as for CH_4 because N_2O is a long-lived gas. All else equal, we would expect the N_2O damage potential to decrease in scenarios with increasing CO_2 emissions. This is because radiative forcing is proportional to the logarithm of carbon dioxide but to the square root of nitrous oxide; at the margin, growth in radiative forcing is proportional to the inverse of the CO_2 concentration and to the inverse to the square root of the N_2O concentration. This distinction is fundamental to the difference between global warming potentials and damage potentials. The former assumes constant concentrations while the latter assumes rising concentrations. Under a scenario with rising concentrations, the damages from incremental N_2O emissions become relatively more important than CO_2. However, as with all of the sensitivity runs for CH_4, without the CO_2 fertilization effect the nitrous oxide damage potentials are more similar across scenarios, between 326 and 366, as the effects on the social costs of both gases vary consistently across scenarios.

Figure 7 shows our estimates of the N_2O damage potential in comparison to earlier estimates (Fankhauser 1994b; Hammitt et al. 1996; Kandlikar 1995; Reilly and Richards 1993; Tol 1999). The histogram shows the 33 previous estimates and the base estimates from this paper with and without carbon dioxide fertilization,

Figure 7: Histogram of our base estimate and our estimate without CO_2 fertilization of the damage potential of nitrous oxide in 2010 (in red) compared to previous estimates



Note that the estimates from this paper are for perturbations in the year 2010, while the estimates from earlier literature represent perturbations in the year 1995 or earlier. Because the social costs of GHGs tend to grow over time, but may not change at identical rates, comparison with earlier estimates is illustrative only.

665 and 376, respectively. Our base estimate is higher than any previous estimate, more than 50% greater than the previous highest estimate.[18]

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[18] As with the estimates for the CH_4 global damage potential, the values shown in Figure 7 are estimates for multiple emissions years and therefore may not be directly comparable. The most recent previous estimates are likely for emissions in 1995 or earlier. Because the social costs of GHGs tend to grow over time, these ratios would also be expected to vary over time. More recent estimates range from 372–394 for emissions in 2010 (Marten and Newbold 2012).

The higher damage potential for nitrous oxide in this work compared to earlier estimates is primarily due to the temporal pattern of radiative forcing between N_2O and CO_2. The incremental radiative forcing of nitrous oxide relative to carbon dioxide starts high and rises for some 30 years after which it continuously falls. Additionally, the pattern of adaptation in *FUND* assumes a greater degree of adaptation and falling vulnerability to climate change with development. Thus, impacts in the more remote future are less pronounced than in other models. These effects together imply that the medium-term damages from nitrous oxide emissions are more important than the longer-term carbon dioxide damages.

3.4 Social Cost of Sulphur Hexafluoride

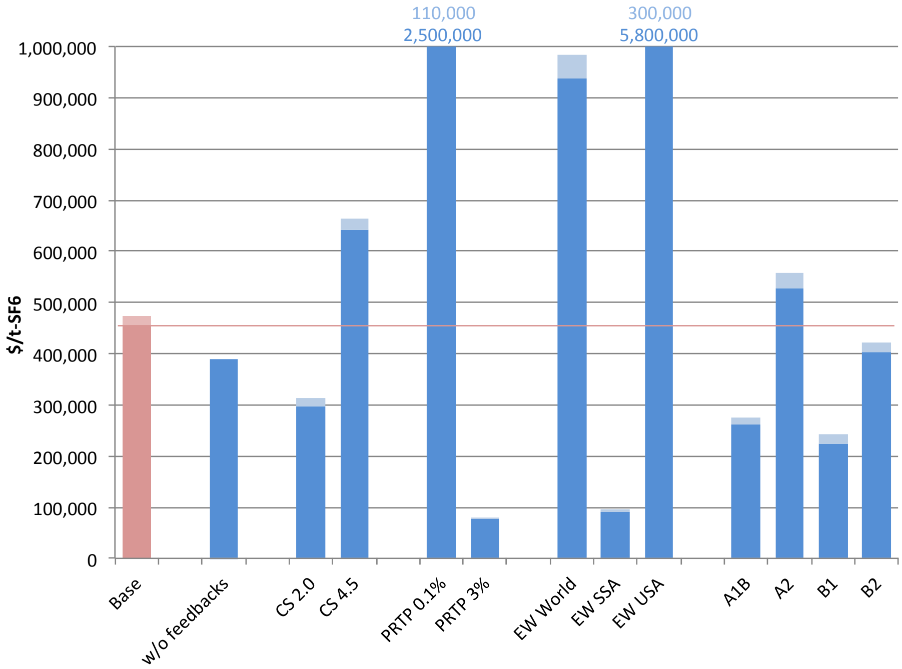
Sulphur hexafluoride is one of the more prominent high-GWP gases and the damage potential for SF_6 may help inform the relative damages from other high GWP gases. Figure 8 shows the social cost of SF_6 under varying assumptions. In the base case, the estimate is \$456,000/tSF_6. Qualitatively, the pattern is similar to that in Figures 1, 2 and 5. Responsiveness of the SC-SF_6 is similar to the social cost of nitrous oxide to most of the assumptions modeled here. One important exception is that the social cost of sulphur hexafluoride is much more responsive to the pure rate of time preference due to its much longer atmospheric lifetime of 3,200 years, compared to 114 years for nitrous oxide and 12 years for methane.

Figure 9 shows the damage potential of sulphur hexafluoride. It is 69,500 in the base case. As with CH_4 and N_2O, the SF_6 damage potential falls to 38,800 without carbon dioxide fertilization because its exclusion only slightly increases the social cost of SF_6 but almost doubles the social cost of CO_2.

The top panel of Figure 9 shows that without the climate change feedback on the terrestrial carbon cycle, the damage potential rises slightly to 75,200. As with methane and nitrous oxide, the SF_6 damage potential with CO_2 fertilization falls to 58,200 and rises to 120,000 with climate sensitivities of 4.5°C and 2.0°C, respectively.

Due to its very long lifetime, SF_6 emissions will continue to have a strong impact on damages for centuries and the SC-SF_6 is therefore relatively more sensitive than the SC-CO_2 to changes in the discount rate. The damage potential for SF_6 is 91,300 using a PRTP of 0.1% and 247,000 when the PRTP is 3.0%/yr.

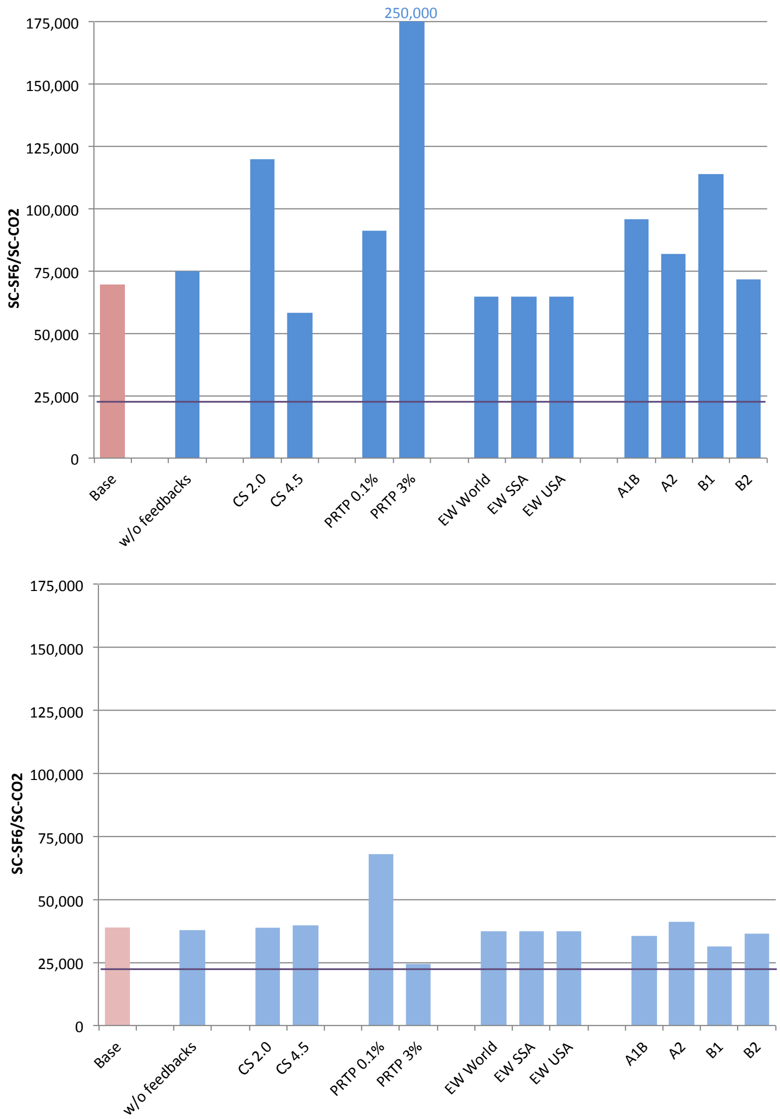
Figure 8: The social costs of sulphur hexafluoride emissions in 2010 (1995$)



Red denotes the estimate with our base assumptions. Darker colours include carbon dioxide fertilization, the sum of the dark and light are estimates without carbon dioxide fertilization. Note that the values for PRTP 0.1% and EW USA exceed the scale of the chart. The bottom number is the value with CO_2 fertilization and the sum of the two values is the value without CO_2 fertilization.

With all forms of equity weighting the SF_6 damage potential falls slightly to 64,900 implying that equity weighting reduces the relative value of SF_6 emissions in the nearer term, in part because impacts in developing regions that tend to occur over shorter time horizons are more heavily valued. The SF_6 damage potential varies across socioeconomic and emissions scenarios with the same general pattern as N_2O, ranging from 71,900 to 114,000 with the SRES B2 and B1 scenarios, respectively. As with the other gases, the damage potential of SF_6 is largely unchanged across the sensitivity runs.

Figure 9: The damage potential of sulphur hexaflouride in 2010 under multiple scenarios



The top panel shows ratios with carbon dioxide fertilization and the bottom panel shows them without carbon dioxide fertilization. The purple line shows the AR4 global warming potential (22,800).

The only other estimate of the SF_6 damage potential is 38,600 (Hope 2006), which is very close to our estimate without carbon dioxide fertilization of 38,800. However, our base estimate of 69,500, which includes CO_2 fertilization, is 80% larger than the Hope estimate. Our base estimate for the SF_6 damage potential is also three times as large as estimates of the GWP. The AR5 and AR4 IPCC 100-year global warming potentials are 23,500 (Myhre et al. 2013) and 22,800 (Forster et al. 2007), respectively and the UNFCCC official value is 23,900 (Schimel et al. 1996). Differences in these estimates are due to the socioeconomic and emissions assumptions under which the values are estimated. As shown in Figure 8, the SF_6 damage potential is quite sensitive to these assumptions. It is particularly sensitive to these conditions because its radiative forcing is linear in its concentration and its extremely long lifetime. In net, these factors cause the social cost of SF_6 to increase much faster than the social cost of carbon dioxide.

4 Discussion and Conclusion

This work presents new estimates of the marginal damage costs of emissions of carbon dioxide, methane, nitrous oxide, and sulphur hexafluoride and estimates of the damage potentials for the three non-CO_2 GHGs. The damage potentials are the ratios of the marginal damage cost of each gas to that of carbon dioxide. These metrics are particularly salient as it is the relative potential for damage, rather than carbon dioxide equivalent value based on global warming potential, that represents the appropriate tradeoffs for marginal reductions of non-CO_2 GHGs. The sensitivity of these results is tested with a variety of assumptions in order to explore the drivers of variation in damage potentials for methane, nitrous oxide, and sulphur hexafluoride.

Under our base case assumptions, the social cost of carbon dioxide is \$6.6/t-CO_2 (1995\$) in 2010 with a pure rate of time preference of 1%. This is in line with previous estimates (Tol 2009b). The inclusion of the benefits of carbon dioxide fertilization on agriculture and forestry in the *FUND* model substantially reduces the social cost of carbon dioxide, while having a relatively minor effect on the social costs of the non-CO_2 greenhouse gases. As a result, our base estimates of the damage potentials for CH_4, N_2O, and SF_6 are at the high end of or substantially higher than previous estimates. When carbon dioxide fertilization is excluded, our estimates of the damage potentials for CH_4 and N_2O are lower, though still on the higher end of previous estimates. Without carbon dioxide fertilization, our estimate for the SF_6 damage potential is roughly equal to the one previous estimate.

For all three of the non-CO_2 GHGs that we analyzed, our base estimates of their damage potentials are higher than their GWPs. In fact, nearly every sensitivity run produced estimates that meet or exceed the AR4 GWPs. The notable exception is that with a very low pure rate of time preference, the CH_4 damage potential declines markedly. This is due to the higher weight given to CO_2 damages, which occur in the more distant future. Interestingly, excluding the benefits of CO_2 fertilization results in damage potentials closer to the GWPs, though our estimates of the damage potentials still exceed the GWPs, with the exception of the CH_4 damage potential estimated with a very low pure rate of time preference.

Our sensitivity results reveal that changes in methane become more important in terms of marginal impacts under lower emissions and less vulnerable conditions. This is because the social cost of CO_2 is lower under these scenarios, which causes the ratio of the social costs of methane to the social costs of carbon dioxide to increase.

Our base estimate of the damage potential of nitrous oxide is larger than all previous estimates because the model assumes substantial adaptation and declining vulnerability with increasing income over time. This causes medium-term incremental impacts to dominate. The temporal pattern of radiative forcing of N_2O relative to CO_2 causes the impacts from N_2O to be most potent in the nearer term and hence discounted less heavily than the longer-term impacts from CO_2 emissions.

The damage potential of sulphur hexafluoride is especially high compared to its global warming potential because the former is evaluated against rising concentrations and the latter against constant concentrations. While this is the case for all greenhouse gases examined here, it matters comparatively more for SF_6 because radiative forcing is linear in its concentration. Combined with SF_6's extremely long atmospheric lifetime, this causes the estimates of the social cost of sulphur hexafluoride to increase faster than the social cost of carbon dioxide.

The results presented here suggest that the social costs of non-CO_2 GHGs should not be estimated by converting the SC-CO with GWPs and, for the three gases examined here, the higher marginal benefits of non-CO_2 emissions reductions have a larger benefit of marginal reduction than would be implied by the GWPs. This result has the potential to alter the relative emphasis placed on GHG mitigation policies.

Finally, there are several caveats to these results. These conclusions are based on a single model and a limited set of sensitivity analyses and are applicable only to the three non-CO_2 greenhouse gases discussed in this paper. Additionally, the model omits the potential damages due to ocean acidification from CO_2. Inclusion of these damages could increase the social cost of carbon dioxide (Brander et al. 2012; Narita et al. 2012), potentially providing additional benefit to incremental carbon dioxide abatement, essentially reducing the damage potentials for the non-CO_2 GHGs. Most importantly, we omit risk from the analysis. Because a portion of carbon dioxide stays in the atmosphere essentially forever, irreversibility and the potential to cross dangerous thresholds may well put a premium on carbon dioxide emissions reduction that is not included in these estimates. These issues are deferred to future research.

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