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

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*Abstract:* We use FUND 3.5 to estimate the social cost of carbon dioxide, methane, nitrous oxide, and sulphur hexafluoride emissions. We show the results of a range of sensitivity analyses, focusing on the impact of carbon dioxide fertilization. Ignored in previous studies of the social cost of greenhouse gas emissions, carbon dioxide fertilization has a positive effect at the margin, but only for carbon dioxide. Because of this, the ratio of the social cost of a greenhouse gas to that of carbon dioxide (the global damage potential) is higher – that is, previous papers underestimated the importance of reducing non-carbon dioxide greenhouse gas emissions. When leaving out carbon dioxide fertilization, our estimate of the social cost of methane is comparable to previous estimates. Our estimate of the global damage potential of methane is close to the estimates of the global warming potential because discounting roughly cancels carbon dioxide fertilization. Our estimate of the social cost of nitrous oxide is higher than previous estimates, also when omitting carbon dioxide fertilization. This is because, in FUND, vulnerability to climate change falls over time (with development) while in the long run carbon dioxide is a more potent greenhouse gas than nitrous oxide. Our estimate of the global damage potential of nitrous oxide is larger than the global warming potential because of carbon dioxide fertilization, discounting, and rising atmospheric concentrations of both gases. Our estimate of the social cost of sulphur hexafluoride is similar to the one previous estimate. Its global damage potential is higher than the global warming potential because of carbon dioxide fertilization, discounting, and rising concentrations.

*Key words:* climate change, social cost, carbon dioxide, methane, nitrous oxide, sulphur hexafluoride

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

## 1. Introduction

Carbon dioxide is the main anthropogenic greenhouse gas, but certainly not the only one. In order to be effective and least cost, climate policy requires the reduction of the emissions of all greenhouse gases (Weyant et al. 2006). This in turn requires a mechanism to understand the potential trade-offs between the various greenhouse gases. There are three ways to compare different greenhouse gases. A physical measure, such as the IPCC's Global Warming Potential (Forster et al. 2007), is often used, however this is essentially random from a decision analytic perspective because it does not weigh the potential welfare changes from emission (reduction) across gases. The ratio of the shadow prices (Manne and Richels 2001) is appropriate when seeking to meet a specific temperature, concentrations, or emissions target at the lowest possible cost. Finally, as is done in this paper, the ratio of marginal impacts should be used if one seeks to maximize welfare.

The appropriate trade-off between greenhouse gases in a cost-benefit framework was recognized in the early 1990s (Eckaus 1992;Michaelis 1992;Schmalensee 1993) and shortly thereafter a number of papers sought to quantify these ratios of the relative global marginal damage potential of greenhouse gas  $i$  with respect to the marginal damage of carbon dioxide (Fankhauser 1995;Hammit et al. 1996;Kandlikar 1995;Kandlikar 1996;Reilly and Richards 1993;Wallis and Lucas 1994), then dubbed the "global damage potential." . Since then, there has been little research (Hope 2006;Tol 1999) even though our understanding of the impacts of climate change has changed dramatically. We therefore revisit the empirical estimates of the global damage potential of methane, nitrous oxide, and sulphur hexafluoride emissions 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, 2010). However, with the legal focus on CO<sub>2</sub> emissions and a dearth of non-CO<sub>2</sub> GHG emission reduction cost estimates, decision-makers have opted to use CO<sub>2</sub> equivalents based on global warming potentials (US EPA, 2008a, 2008b) or, more recently, not value changes in non-CO<sub>2</sub> GHG emissions at all (USDoE 2010) due to the recognition that the GWP ratios may not be the correct transformation to use for the global damage potentials. This paper will help inform this issue by providing direct estimates of these potentials.

The paper continues as follows: Section 2 presents the model, Section 3 discusses the results, and Section 4 concludes.

## 2. The model

The results in this paper are generated with version 3.5 of the *Climate Framework for Uncertainty, Negotiation and Distribution (FUND)*. Version 3.5 of *FUND* corresponds to version 1.6 (Tol et al. 1999;Tol 2001;Tol 2002c) except for the impact module which now includes diarrhoea and tropical and extratropical storms (Link and Tol 2004;Narita et al.

2009;Narita et al. 2010;Tol 2002a;Tol 2002b). 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/>.

The model distinguishes 16 major regions of the world, viz. 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 time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. 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.<sup>1</sup> The centuries after the 21<sup>st</sup> are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2300.

The scenarios are defined by exogenous assumptions on the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from fossil fuel 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 impact of climatic change. 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>). 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. Immigrants are assumed to assimilate immediately and completely with the respective host population.

*FUND* derives atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric

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<sup>1</sup> 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 2000–2010 period is interpolated from the immediate past (<http://earthtrends.wri.org>), and the period 2100–3000 extrapolated.

concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model (Hammit et al. 1992;Maier-Reimer and Hasselmann 1987). The model also contains sulphur emissions (Tol 2006).

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is as in the IPCC (Ramaswamy et al. 2001). The global mean temperature  $T$  is governed by a geometric build-up to its equilibrium (determined by the radiative forcing  $RF$ ), with an e-folding time of 66 years. In the base case, 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 an e-folding time of 500 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario (Kattenberg et al. 1996).

The climate impact module includes the following 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).

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. 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 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).

Vulnerability to climate change 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). The income elasticities (Tol 2002b) are estimated from cross-sectional data or taken from the literature.

We estimated the SCC cost of carbon by computing the total, monetised impact of climate change along a business as usual path and along a path with slightly higher emissions between 2010 and 2019.<sup>2</sup> Differences in monetized damages from climate change impacts were calculated, discounted back to the current year, and normalised by the difference in emissions.<sup>3</sup> The SCC is thereby expressed in 1995 dollars per tonne of carbon at a point in time (2010)—the standard measure of the additional impacts globally and over time of an additional global tonne of emissions. 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:

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

$$\delta_t = \begin{cases} \omega & \text{for } 2010 \leq t < 220 \\ 0 & \text{for all other cases} \end{cases}$$

where,

<sup>2</sup> The social cost of emissions in future or past periods is beyond the scope of this paper.

<sup>3</sup> We abstained from levelizing the incremental impacts within the period 2010–2019 because the numerical effect of this correction is minimal while it is hard to explain.

- $SCC_{r,i}$  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 US dollars per year);
- $E$  are emissions of greenhouse gas  $i$  (in metric tonnes of  $i$  per year);
- $\delta$  are incremental emissions (in metric tonnes of  $i$  per year);
- $\omega$  are increment emissions (in metric tonnes of  $i$  per year);
- $\rho$  is the pure rate of time preference (in fraction per year);
- $\eta$  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  $SCC_i$  per region, and then aggregate, as follows

$$SCC_i = \sum_{r=1}^{16} \left( \frac{Y_{2010,ref}}{Y_{2010,r}} \right)^\varepsilon SCC_{r,i} \quad (2)$$

where

- $SCC_i$  is the global social cost of greenhouse gas  $i$  (in 1995 US dollars per tonne of  $i$ );
- $SCC_{r,i}$  is the regional social cost of greenhouse gas  $i$  (in 1995 US dollars per tonne of  $i$ );
- $r$  denotes region;
- $i$  denotes greenhouse gas;
- $Y_{ref}$  is the average per capita consumption in the reference region (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);
- $Y_r$  is the regional average per capita consumption (in US dollars per person per year); and
- $\varepsilon$  is the rate of inequity aversion;  $\varepsilon = 0$  in the case without equity weighing;  $\varepsilon = \eta$  in the case with equity weighing.

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

$$GDP_i = \frac{SCC_i}{SCC_{CO_2}} \quad (3)$$

where

- $GDP_i$  is the global damage potential of greenhouse gas  $i$  (unitless);
- $SCC_i$  is the global social cost of greenhouse gas  $i$  (in US dollars per tonne of  $i$ ); and

- $i$  denotes greenhouse gas.

Because the impact of non-CO<sub>2</sub> GHGs differs from CO<sub>2</sub> with respect to carbon dioxide fertilization, it is useful to split the social cost of carbon dioxide into the social cost of carbon dioxide through its effect on climate change and its fertilization effect.

$$GDP_i = \frac{SCC_i}{SCC_{CO_2}} =: \frac{SCC_i}{SCC_{CO_2}^{cc} + SCC_{CO_2}^{fert}} =: \frac{f_i(\mathcal{G}, \varphi)}{f_{CO_2}(\mathcal{G}, \varphi) + g_{CO_2}(\mathcal{G}, \psi)} \quad (4)$$

Equation (4) is an expansion of Equation (3), highlighting that the social cost of carbon dioxide through climate change and the social cost of other greenhouse gases are similar functions of the same vector of parameters. The social cost of carbon dioxide through fertilization is a different function with partly overlapping parameters. This implies that, without carbon dioxide fertilization, one would expect the global damage of greenhouse gas  $i$  with respect to the social cost of carbon dioxide potential to be largely robust to parameter variations. 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 the social costs of carbon dioxide. The base case estimate is \$8/tCO<sub>2</sub>. This number depends on a large number of assumptions. Here we examine the sensitivity of this estimate with respect to carbon dioxide fertilization, tropical forest dieback, climate sensitivity, pure rate of time preference, equity weights, and socio-economic and emissions scenarios.

The SCC is reasonably low because of the positive effects of carbon dioxide fertilization on agriculture. If we turn that off, the social cost rises to \$14/tCO<sub>2</sub>. The carbon dioxide fertilization effect is comparatively large because it occurs in the near future, thus having a relatively larger effect on the net present value than the negative impacts that occur in later time periods.

On the other hand, the social cost estimate is pushed up because the base case assumes that, because of climate change, tropical forests will die back and release substantial amounts of carbon dioxide. If we turn that off, the social cost falls to \$7/tCO<sub>2</sub>. Compared to the carbon dioxide fertilization effect, this effect is relatively small because it occurs in the distant future, thus discounted more heavily.

The climate sensitivity, or the equilibrium warming due to a doubling of carbon dioxide concentrations, has a larger effect on the SCC estimates. In the base case, we assume a climate sensitivity of 3.0°C equilibrium warming due to a doubling of ambient carbon dioxide. If we use climate sensitivities of 2.0°C or 4.5°C instead, the social cost falls to \$3/tCO<sub>2</sub> and rises to \$18/tCO<sub>2</sub>, respectively.

Assumptions about the discount rate have an even larger effect on the estimates. In the base case, the pure rate of time preference is 1% per year. If instead we use a pure rate of time preference of 0.1% or 3% per year, the social cost rises to \$51/tCO<sub>2</sub> or falls to only \$0.3/tCO<sub>2</sub>, respectively. Additionally, the base case does not use equity weights. If world-average equity weights are used instead, the social cost rises to \$25/tCO<sub>2</sub>. If, instead, US or sub-Saharan African equity weights are used, the social cost estimates are \$154/tCO<sub>2</sub> and \$2/tCO<sub>2</sub>, respectively.

Finally, the base case scenario uses population, income, and emissions according to the FUND scenario. If the SRES scenarios (Nakicenovic and Swart 2001) are used instead, the social cost is \$2/tCO<sub>2</sub> for the B1 scenario which is a low emissions/low growth scenario, \$3/tCO<sub>2</sub> for A1B which represents a high emissions/low growth world, \$8/tCO<sub>2</sub> for B2 which has low emissions and high growth, or \$12/tCO<sub>2</sub> for A2, the high emissions/high growth world. 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 the level of economic growth, because the valuation of impacts is measured as a function of income.

### *3.2. Social Cost of Methane*

The social costs of methane emissions are shown in Figure 2. As for SC-CO<sub>2</sub>, the sensitivity of SC-CH<sub>4</sub> is estimated with respect to a number of assumptions. In the base case, the estimate is \$205/tCH<sub>4</sub>. As one would expect, the qualitative pattern is the same as in Figure 1. The impacts of climate change respond in the same way to parameter variations regardless of whether climate change is caused by methane or carbon dioxide. One difference is that the social cost of methane is only slightly higher without carbon dioxide fertilization than with. The reason is that the methane does not have the positive effects of carbon fertilization, so economic growth is slightly slower and people are a bit more vulnerable to climate change.

Figure 3 shows the global damage potential, that is, the ratio of the social cost of methane to the social cost of carbon dioxide. In the base case, the estimated damage from emitting an additional tonne of methane is 25 times more than the damage from emitting an additional tonne of carbon dioxide. As seen in Figure 3, the global damage potential for methane varies with the assumptions described above. Without carbon dioxide fertilization, carbon dioxide is a lot more damaging and methane only slightly more, so that the global damage potential falls to 16. Because carbon dioxide fertilization is such a large part of the social cost of carbon dioxide (cf. Figure 1), Figure 3 shows the global damage potential with and without carbon dioxide fertilization for changes in each of these assumptions.

The feedback of climate change on the terrestrial carbon cycle has the same proportional effect on the social costs of methane and carbon dioxide; the global damage potential hardly changes. The climate sensitivity is more important for a long-lived gas such as carbon dioxide than for a short-lived gas such as methane so the global damage potential falls to 19 when the climate sensitivity is 4.5°C and rises to 40 with a climate sensitivity of 2.0°C. This effect is largely due to carbon dioxide fertilization.



The same effect, but stronger, is observed for variations in the pure rate of time preference. The global damage potential falls to 9 for a pure rate of time preference of 0.1% and rises to 221 as the pure rate of time preference is increased to 3.0%/yr. Again, this is amplified by carbon dioxide fertilization.

Equity weighting is therefore more important for carbon dioxide, and the global damage potential falls to 22 using global equity weights. This is because poor countries contribute less to the marginal impact during the short life-time of methane than during the long life-time of carbon dioxide. The same, but weaker effect is observed without carbon dioxide fertilization.

Similarly, the differences between scenarios are more pronounced in the long term and hence have a greater effect on longer lived gases and the social cost of carbon dioxide. The global damage potential therefore varies considerably between scenarios, ranging between 20 and 55 for the A2 and B1 scenarios, respectively. Again, carbon fertilization strengthens the differences. Note that methane is relatively more potent on the margin in the A1B and B1 scenarios, where emissions are relatively lower and society richer and more equal than the other scenarios. In these contexts, society is more sensitive to changes in methane emissions.

Figure 4 shows our estimates of the global 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). The 61 previous estimates are shown as the empirical cumulative density function in blue. Without carbon dioxide fertilization, our base estimate of the global damage potential for methane is 16, with a range of 7 to 25. The base estimate is the 57<sup>th</sup> percentile of previous estimates, falling in the middle of the range of earlier work which did not include the effects of carbon dioxide fertilization. However, the primary estimate which includes carbon dioxide fertilization, is 25, with a range of 8 to 221. Therefore the primary estimate in this work is at the 82<sup>nd</sup> percentile – on the high side due to the explicit modeling of the CO<sub>2</sub> fertilization processes for the different gases.

The latest IPCC 100-year global warming potential (GWP) estimate is 25 (Forster et al. 2007) and the official UNFCCC estimate is 21 (Schimel et al. 1996). The GWP estimates are comparable to our base estimate of the global damage potential with CO<sub>2</sub> fertilization. However, the GWP estimates appear high relative to the scenarios with less favorable circumstances in the future (e.g., high climate sensitivity, higher emissions, and more vulnerable populations) and low relative to scenarios with more favorable circumstances. In our estimates without carbon dioxide fertilization, the global damage potential is lower than the global warming potential estimates because the benefits in the near term from CO<sub>2</sub> fertilization are not reaped for the SC-CO<sub>2</sub> and these losses are not proportional in the SC-CH<sub>4</sub>, which has a much smaller benefit from CO<sub>2</sub> fertilization in the base case.

### 3.3. Social Cost of Nitrous Oxide

Figure 5 shows the social cost of nitrous oxide emissions. The estimate is \$5,900/tN<sub>2</sub>O 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, the climate sensitivity, and the socioeconomic scenario, all of which have stronger impacts in the long term.

Figure 6 shows the global damage potential of nitrous oxide. In the base case the net present value of the damage from nitrous oxide is 713 times more than for carbon dioxide. Without the effect of carbon dioxide fertilization, the estimate falls to 437. Eliminating the climate change feedback on the terrestrial carbon cycle causes the global damage potential to rise slightly to 748.

As with the pattern for methane, the global damage potential falls to 572 and rises to 1162 as the climate sensitivity is changed to 4.5°C or 2.0°C, respectively. Without carbon dioxide fertilization, 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.

As the pure rate of time preference is changed to 0.1%/yr and 3.0%/yr, while maintaining the other base case assumptions, the global damage potential falls to 449 and rises to 3503, respectively. Without carbon dioxide fertilization, however, the global damage potential is highest for the middle pure rate of time preference, as there is more carbon dioxide (relative to the initial pulse) than nitrous oxide in both the short run and the very long run – this follows from the pattern of atmospheric decomposition of the two gases. However, with carbon dioxide fertilization the global damage potential is highest for the highest pure rate of time preference because the initial benefits of carbon dioxide fertilization are more pronounced compared to the longer term damages of both gases which are discounted more heavily. As with methane, the global damage potential falls with equity weighting, from 713 to 645, because the positive impact of carbon dioxide fertilization weighs more heavily.

As would be expected, the global damage potential varies between scenarios, ranging from 648 (A2) to 1281 (B1) with CO<sub>2</sub> fertilization. It is lowest in scenarios with higher economic growth and carbon dioxide emissions because the absolute value of agriculture (and hence CO<sub>2</sub> fertilization) is higher in richer scenarios and because radiative forcing is proportional to the logarithm of carbon dioxide but to the square root of nitrous oxide. Without the fertilization effect, though, the nitrous oxide damage potentials are very similar across scenarios, between 383 and 437, because the changes in damages due to varying levels of economic development and carbon emissions are essentially cancelled out.

Figure 7 shows our estimates of the global damage potential of nitrous oxide in comparison to earlier estimates (Fankhauser 1994b; Hammitt et al. 1996; Kandlikar 1995; Reilly and Richards 1993; Tol 1999). The 33 previous estimates are shown as the empirical cumulative

density function. Without carbon dioxide fertilization, our base estimate is 437, with a range of 367 to 438. Our base estimate is higher than any previous estimate. It is also much higher than the most recent IPCC 100-year global warming potential of 298 (Forster et al. 2007), and the official UNFCCC value of 310 (Schimel et al. 1996). Figure 6 shows that the global damage potential of nitrous oxide decreases as carbon dioxide emissions are higher – this is because radiative forcing is proportional to the logarithm of carbon dioxide but to the square root of nitrous oxide. An additional difference between global warming potentials and global damage potentials is that the former assumes constant concentrations while the latter assumes rising concentrations. Under a scenario with rising concentrations, the damages from nitrous oxide become relatively more important. Finally, discounting reduces the importance of impacts in the long run when the damages from carbon dioxide dominate those of nitrous oxide.

The higher global damage potential for nitrous oxide in this work compared to earlier estimates is due to the temporal pattern of radiative forcing between  $N_2O$  and  $CO_2$  and the pattern of adaptation in *FUND*. 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, as *FUND* assumes a greater degree of adaptation and falling vulnerability to climate change with development, 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 of the high-GWP gases. Figure 8 shows the social cost of  $SF_6$  under varying assumptions. In the base case, the estimate is \$519,000/t $SF_6$ . Qualitatively, the pattern is similar to that in Figures 1, 2 and 4. 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 more responsive to the pure rate of time preference due to its much long atmospheric lifetime of 3,200 years, as opposed to 114 years for nitrous oxide and 12 years for methane.

Figure 9 shows the global damage potential of sulphur hexafluoride. It is 62,700 in the base case. Without carbon dioxide fertilization, it falls to 38,300 because a lack of carbon dioxide fertilization only slightly increases the social cost of  $SF_6$  but almost doubles the social cost of  $CO_2$ . Without the climate change feedback on the terrestrial carbon cycle, the global damage potential rises slightly to 65,200. As with methane and nitrous oxide, the global damage potential with  $CO_2$  fertilization falls to 55,900 and rises to 99,400 with climate sensitivities of 4.5°C and 2.0°C, respectively.

With a pure rate of time preference of 0.1% the global damage potential is 84,700 and 208,700 when the pure rate of time preference is 3.0%/yr. This reflects the long life time of sulphur hexafluoride where damages from emissions today continue to have a strong impact for centuries and are therefore relatively more sensitive than  $CO_2$  to lower pure rates of

time preference. The global damage potential falls (to 56,900) with all forms of equity weighting, implying that equity weighting reduces the relative value of SF<sub>6</sub> emissions in the nearer term, most likely because impacts in developing regions that tend to occur over shorter time horizons are more heavily valued. The global damage potential varies between scenarios, ranging from a low of 62,700 using the FUND scenario, to 102,000 with the SRES B1 scenario (which is poorer and therefore more vulnerable). Carbon dioxide fertilization again enhances the differences between the scenarios.

The only other estimate of the global damage potential (Hope 2006) is 38,600, which is very close to our estimate without carbon dioxide fertilization. The latest IPCC 100-year global warming potential is 22,800 (Forster et al. 2007) and the UNFCCC official value is 23,900 (Schimel et al. 1996). These differences are due to the socioeconomic and emissions assumptions under which the values are estimated. Figure 8 shows that the global damage potential is negatively correlated with socioeconomic and emissions scenarios, because the global warming potential is evaluated with constant concentrations – or rather because radiative forcing is proportional to the logarithm of the atmospheric concentration carbon dioxide but proportional to the concentration of sulphur hexafluoride.

#### 4. Discussion and conclusion

We estimate the marginal damage cost of emissions of carbon dioxide, methane, nitrous oxide, and sulphur hexafluoride. We also report the global damage potentials, that is, the ratios of the marginal damage costs to that of carbon dioxide. We do this because it is the global damage potentials, rather than carbon dioxide equivalent values based on global warming potentials, that represent the appropriate trade-off between greenhouse gases in a cost-benefit analysis. These values are estimated for a range of scenarios and parameter specifications in order to explore the drivers of variation in global damage potentials across these gases.

Under our base case assumptions, the social cost of carbon dioxide is \$8/tCO<sub>2</sub> in 2010 for a pure rate of time preference of 1%, well in line with previous estimates (Tol 2009). The inclusion of the positive effects of carbon dioxide fertilization on agriculture and forestry in the *FUND* model substantially reduces the social cost of carbon dioxide, while having very little effect on the social costs of the other greenhouse gases. As a result, our estimates of the global damage potentials are substantially higher than previous estimates under our base case assumptions. If we exclude carbon dioxide fertilization, our estimates for methane and sulphur hexafluoride are more comparable with previous estimates of the global damage potential. Our base estimate for methane's global damage potential is low compared to its global warming potential because the incremental impacts are smaller in the short run when temperature changes are lower. However, 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<sub>2</sub> is lower under these scenarios, which causes the ratio of methane to carbon dioxide to increase.

Our estimate of the global damage potential of nitrous oxide is higher than previous estimates because the model assumes substantial acclimatization and falling vulnerability so that medium-term incremental impacts are dominant. The temporal pattern of radiative forcing of N<sub>2</sub>O relative to CO<sub>2</sub> causes the impacts from N<sub>2</sub>O to be most potent in the nearer term, and hence discounted less heavily than the longer term impacts from CO<sub>2</sub> emissions.

The global 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 true for all greenhouse gases, it matters particularly for SF<sub>6</sub> because radiative forcing is linear in its concentration. This is combined with SF<sub>6</sub>'s extremely long lifetime of 3,200 years which 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, based on the higher marginal benefits of non-CO<sub>2</sub> emissions reductions compared with the marginal benefit of CO<sub>2</sub> reductions, climate policy would benefit from placing more emphasis on abatement of the three non-carbon dioxide greenhouse gases examined here than using a simple CO<sub>2</sub> equivalent conversion would suggest.

There are, however, a number of caveats to these results. These conclusions are based on a single model and a limited set of sensitivity analyses and are applicable to only the three non-CO<sub>2</sub> greenhouse gases discussed in this paper. More importantly, we omit uncertainty from the analysis. Because part 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 emission reduction. Additionally, the model omits the damages due to ocean acidification from CO<sub>2</sub>. Inclusion of these damages would likely increase the social cost of carbon dioxide, providing another reason to favour carbon dioxide abatement over non-CO<sub>2</sub> greenhouse gases, essentially lowering their global damage potentials. However, these matters are deferred to future research.

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## Figures

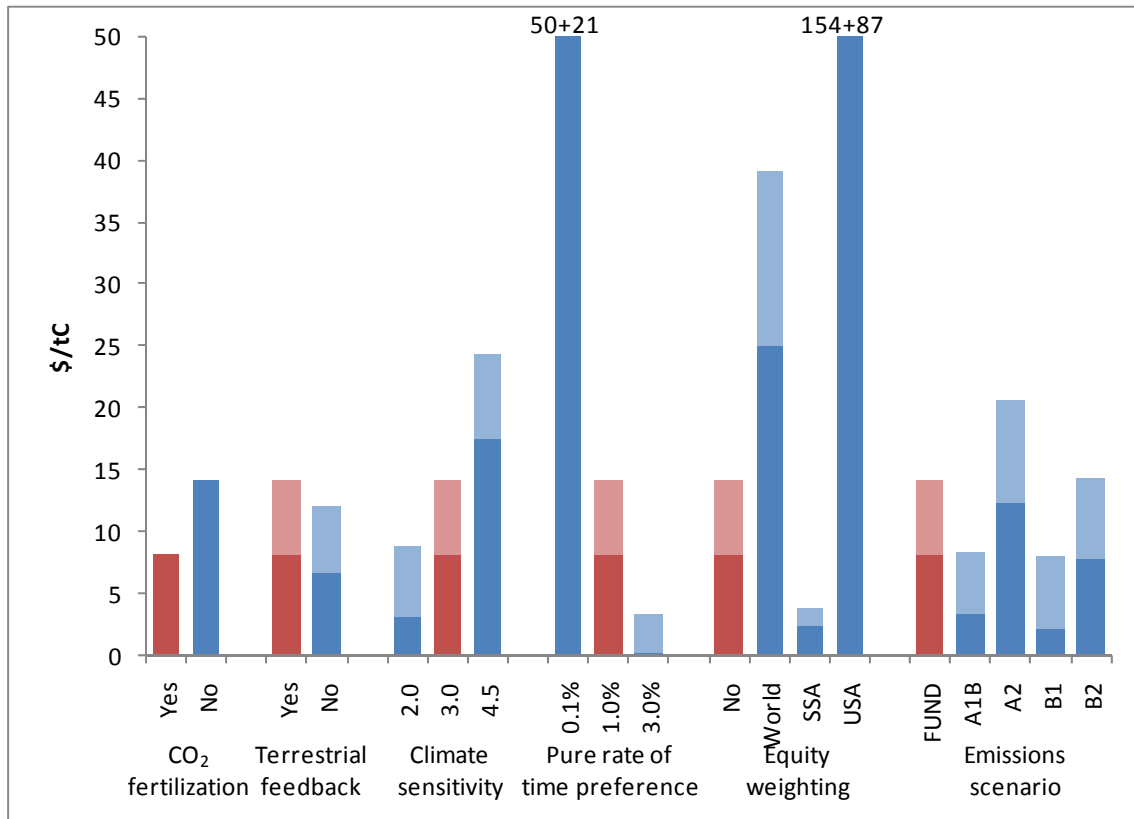


Figure 1. The social cost of carbon dioxide emissions. Red denotes the estimate with our base assumptions for each parameter. The darker colours are with carbon dioxide fertilization; the total columns are without carbon dioxide fertilization; the lighter colours are the difference.

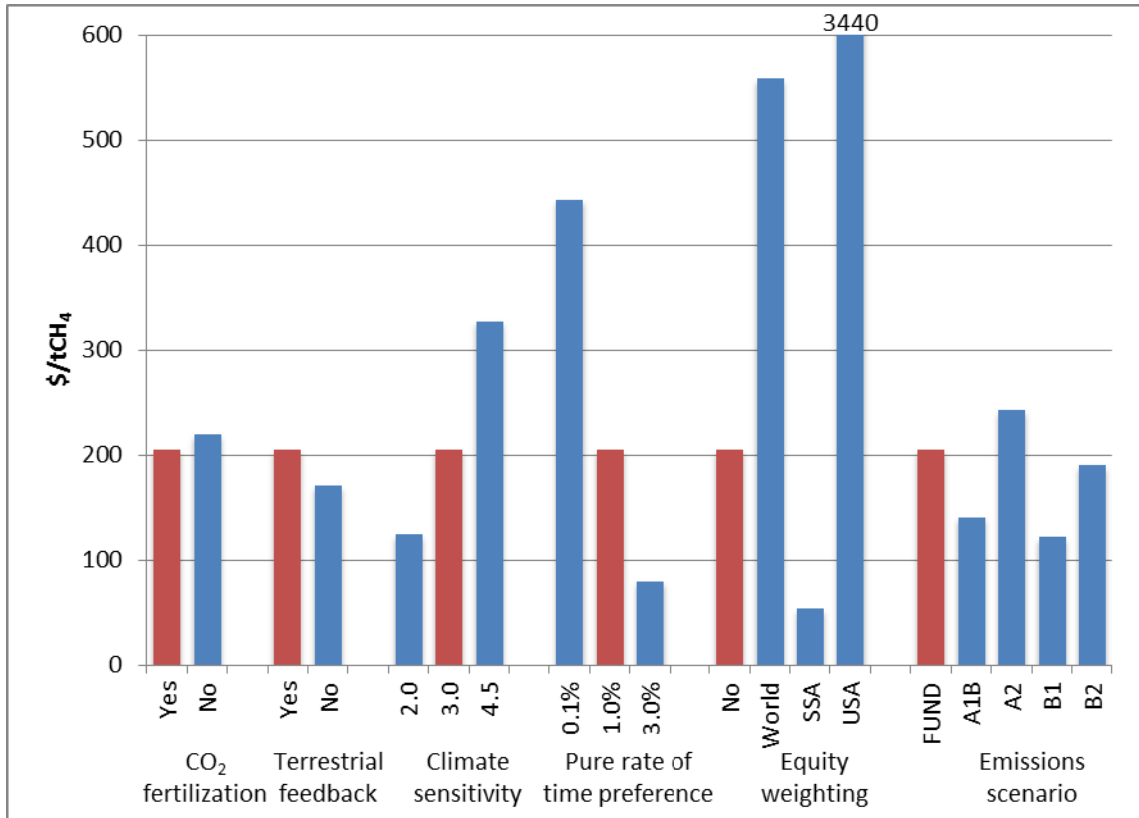


Figure 2. The social costs of methane emissions. Red denotes the base assumptions.

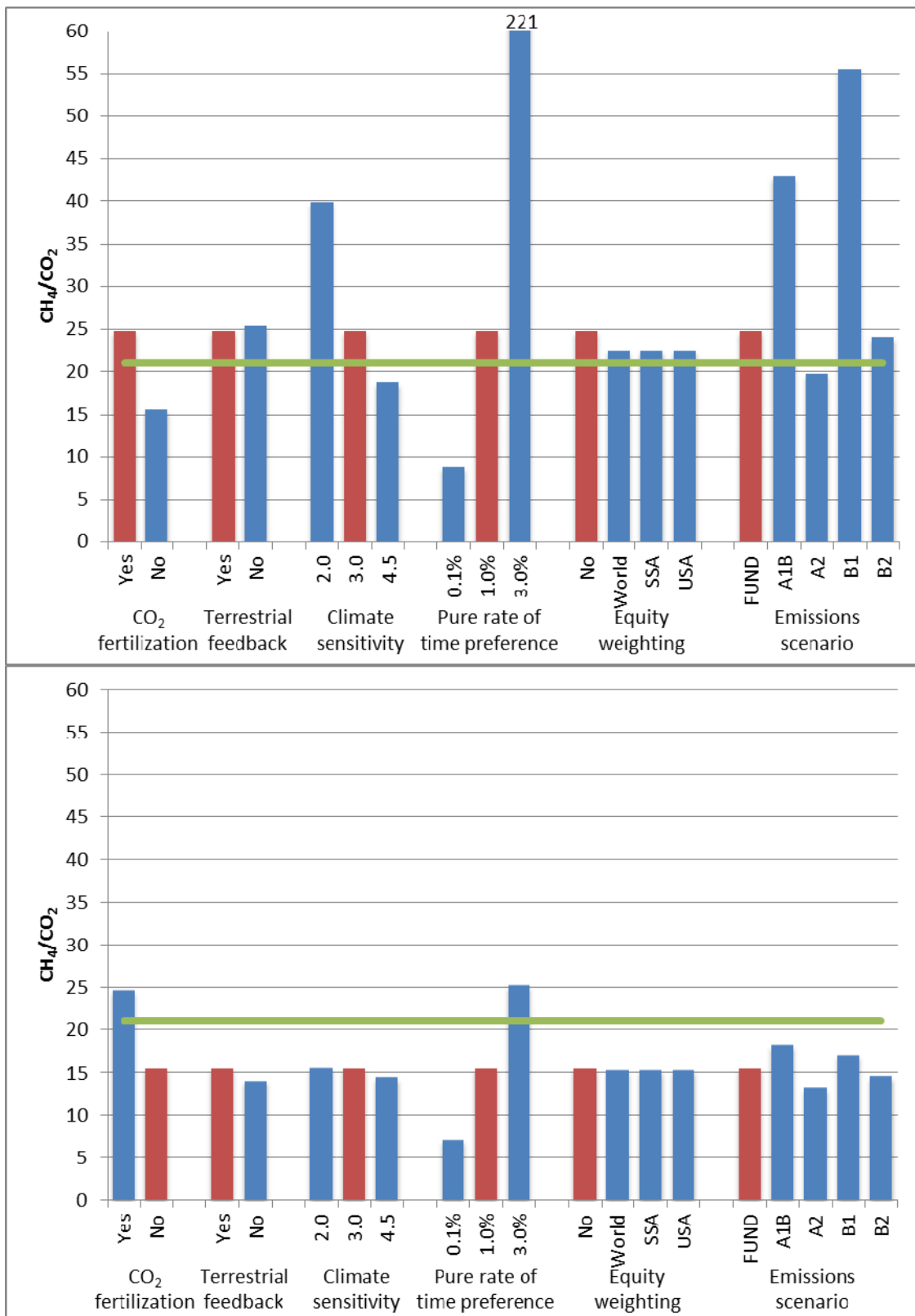


Figure 3. The global damage potential of methane; for comparison, the global warming potential is shown as well (green line); top panel: carbon dioxide fertilization; bottom panel: no carbon dioxide fertilization.



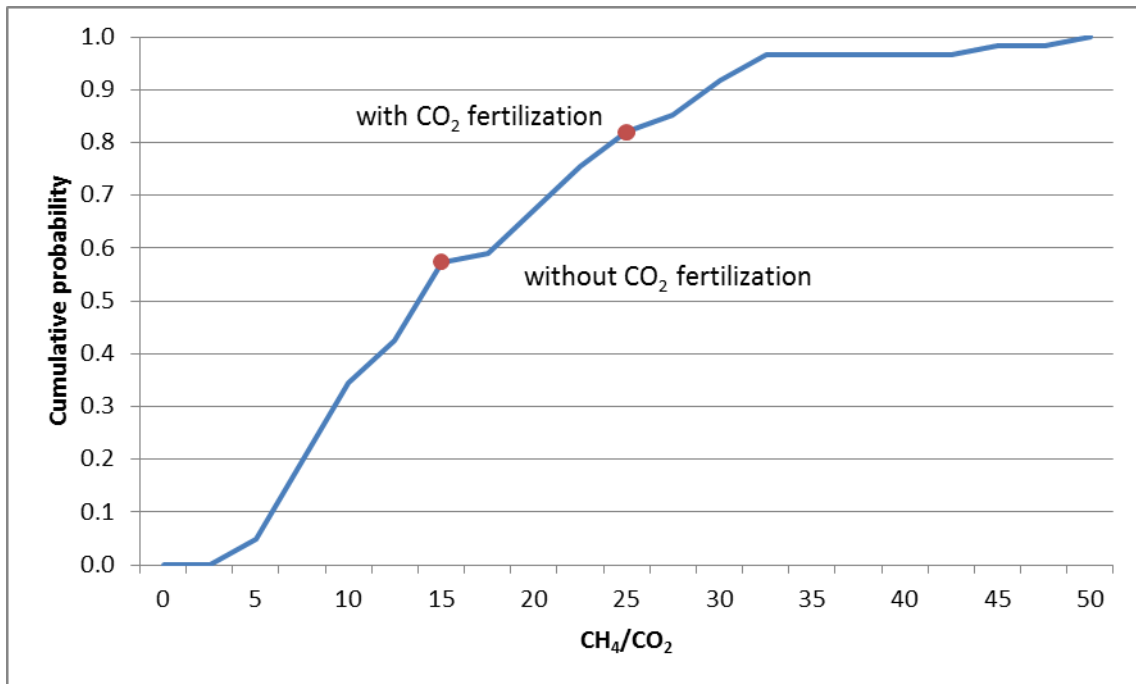


Figure 4. Our base estimates of the global damage potential of methane (red dots) compared to previous estimates (cumulative density function).

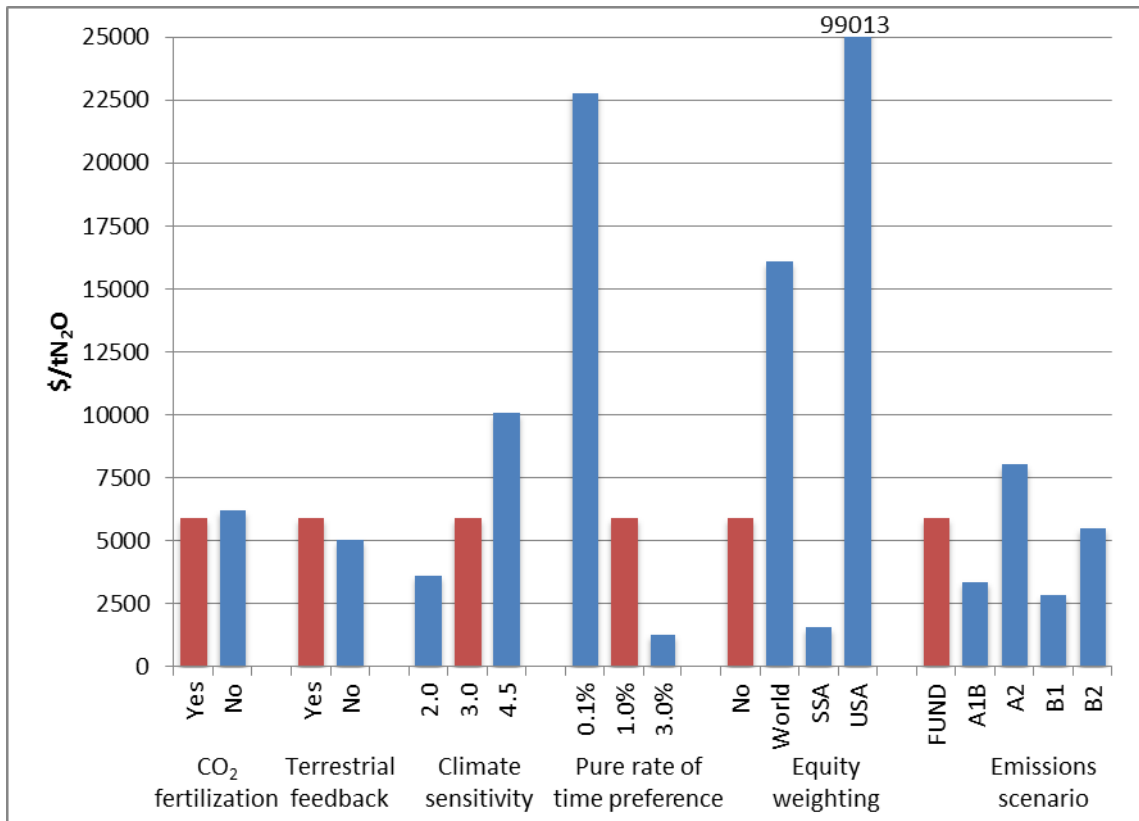


Figure 5. The social cost of nitrous oxide emissions. Red denotes the estimate with our base assumptions.

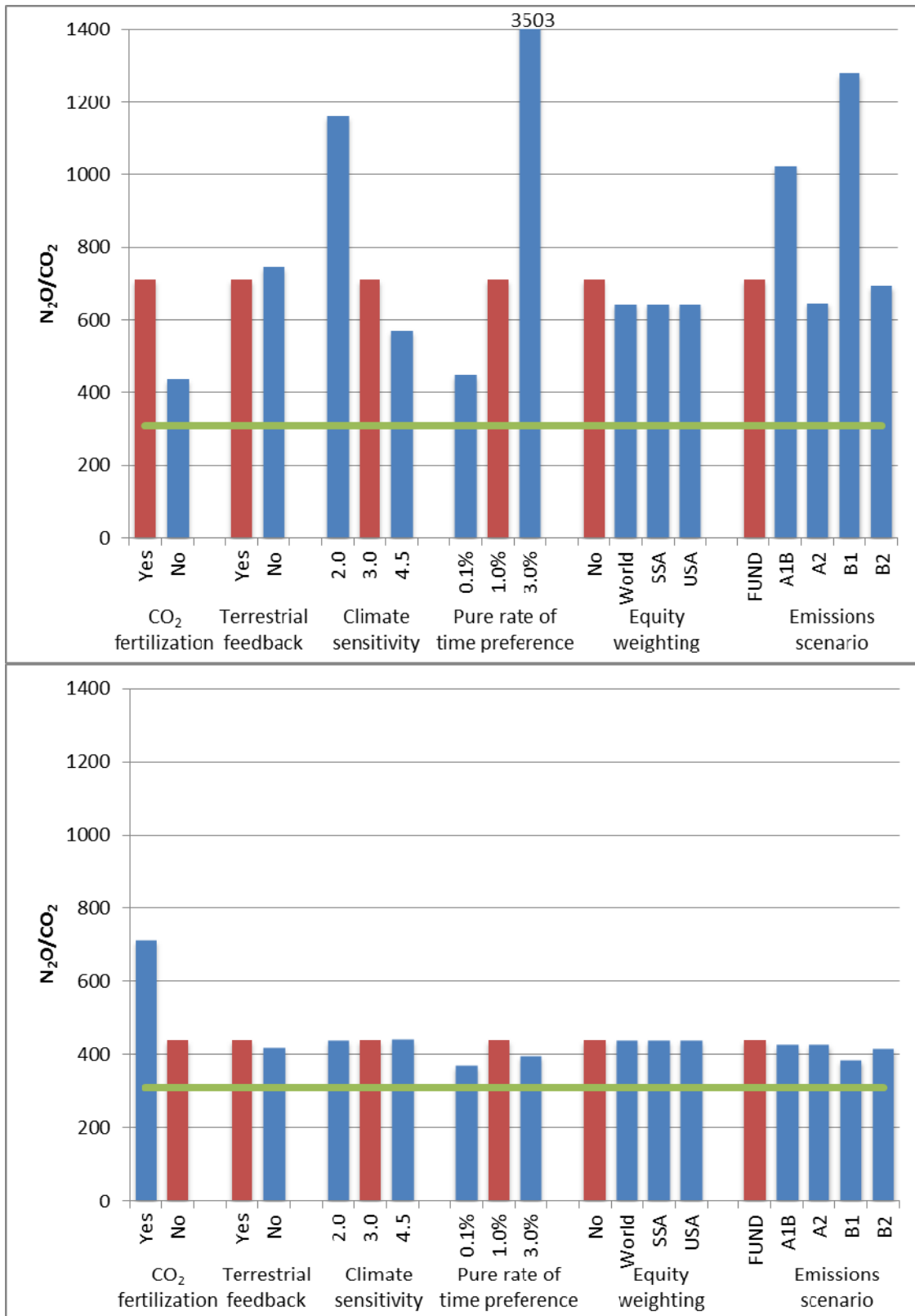


Figure 6. The global damage potential of nitrous oxide; for comparison, the global warming potential is shown as well (green line); top panel: with carbon dioxide fertilization; bottom panel: with no carbon dioxide fertilization.

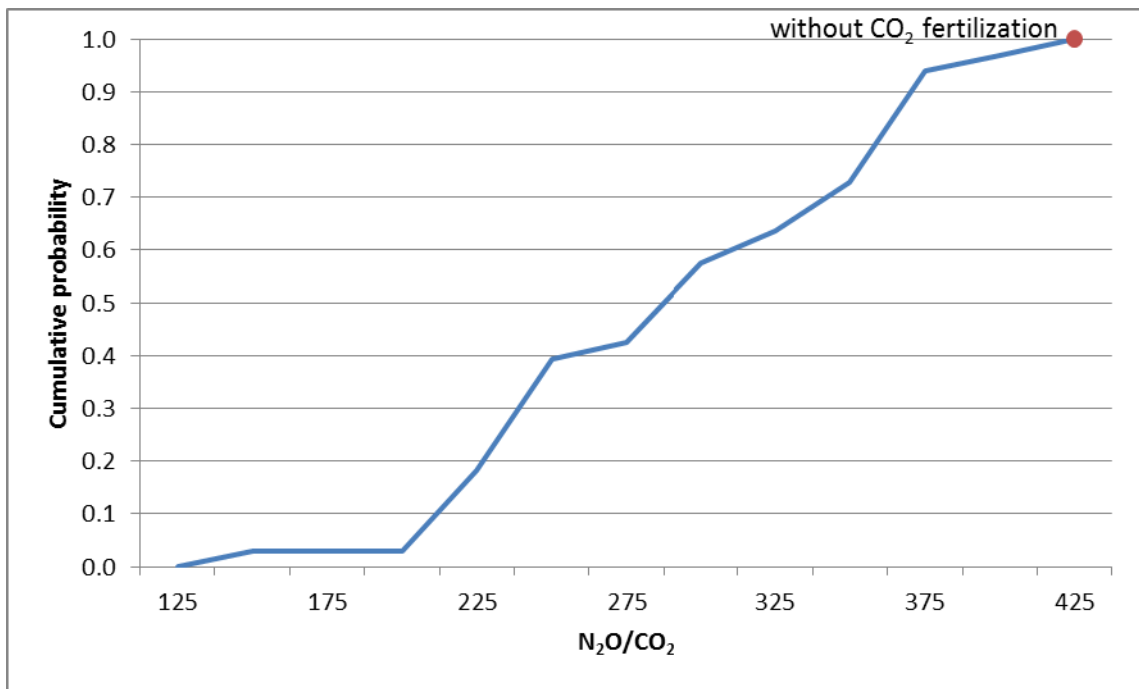


Figure 7. Our estimate of the global damage potential of nitrous oxide (red dot) compared to previous estimates (cumulative density function).

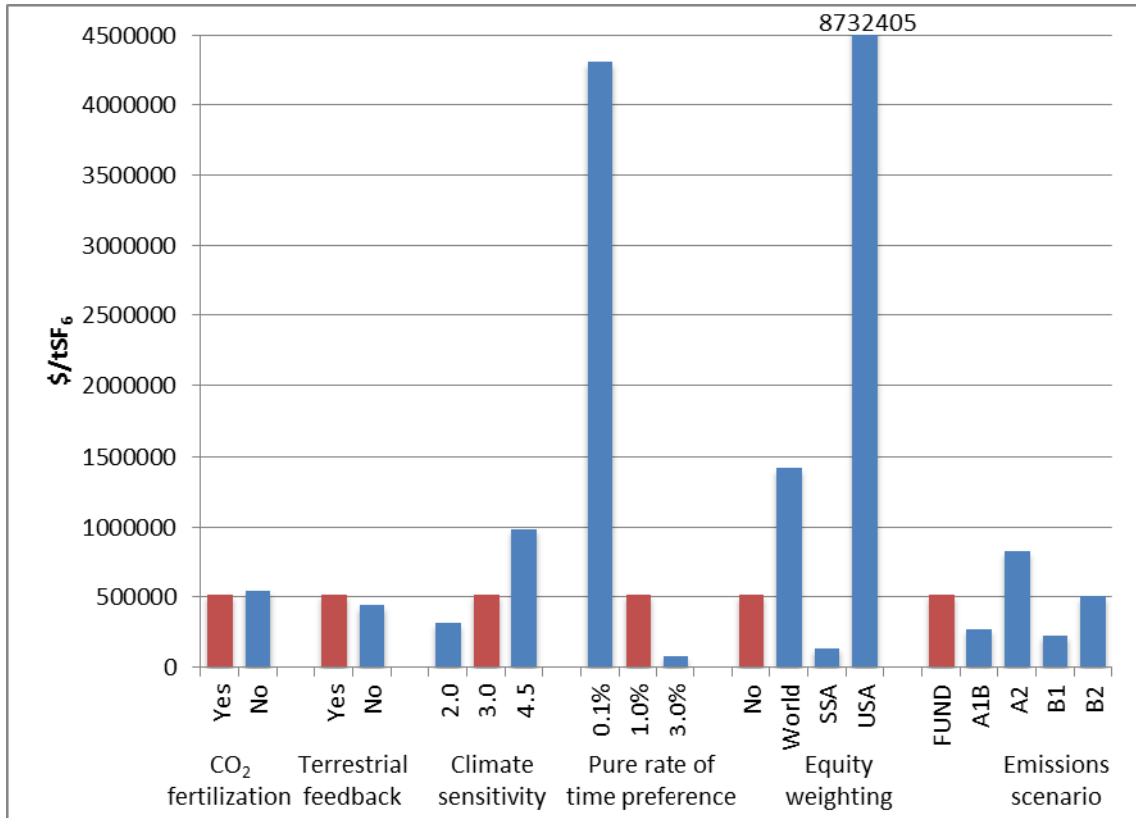


Figure 8. The social costs of sulphurhexafluoride emissions. Red denotes the estimate with our base assumptions.

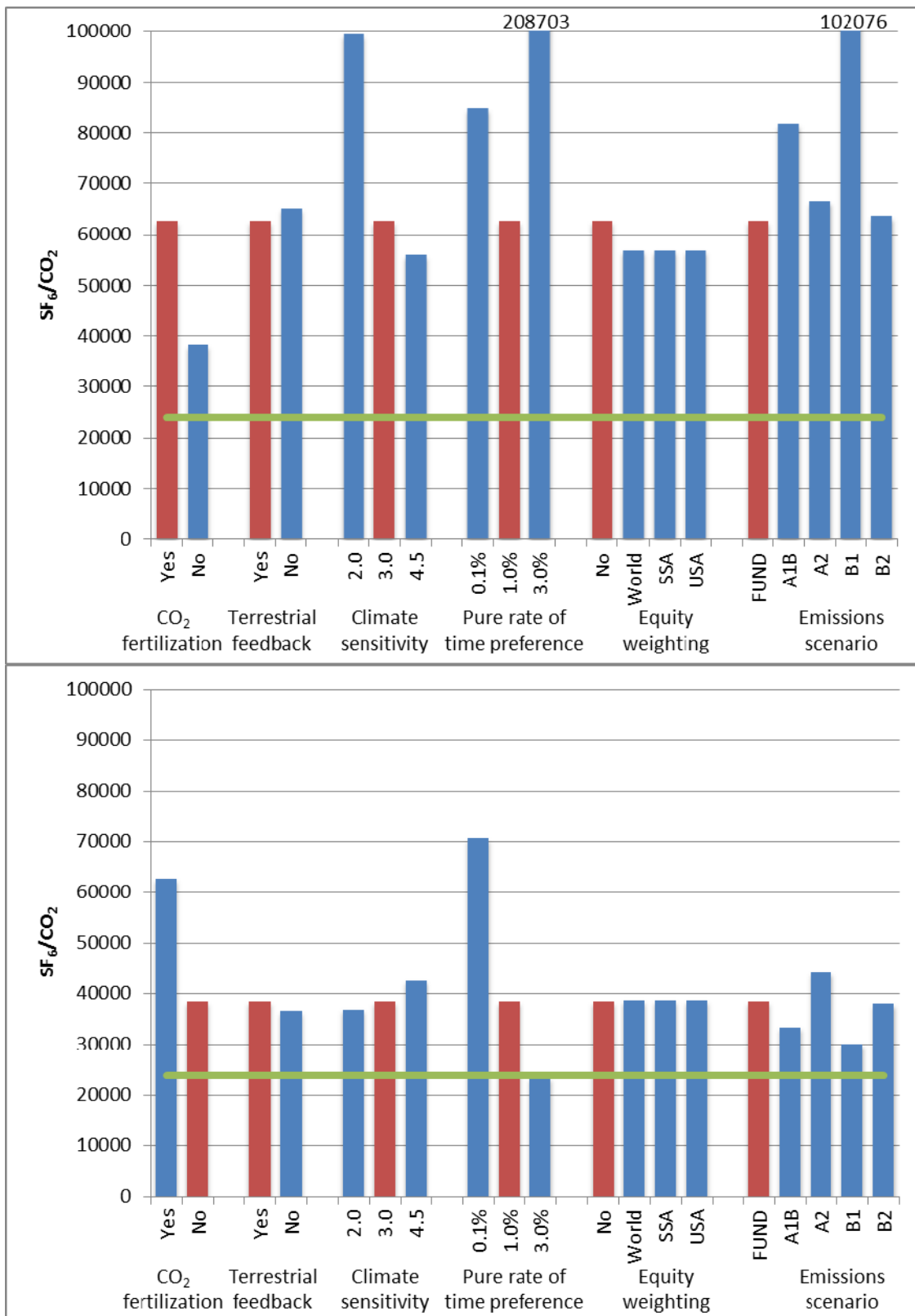


Figure 9. The global damage potential of sulphurhexafluoride; for comparison the global warming potential is shown as well (green line); top panel: carbon dioxide fertilization; bottom panel: no carbon dioxide fertilization.

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