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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.

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1. Introduction

Carbon dioxide is the main anthropogenic greenhouse gas, but certainly not the only one. Effective and cheap climate policy requires the reduction of the emissions of all greenhouse gases (Weyant et al. 2006). This in turn requires a mechanism to trade-off the various greenhouse gases against one another. There are three ways to compare different greenhouse gases. One can use a physical measure (Forster et al. 2007), which is essentially random from a decision analytic perspective. One can use the ratio of the shadow prices (Manne and Richels 2001), which is appropriate if one seeks to meet a certain temperature, concentrations, or emissions target at the lowest possible cost. As is done in this paper, one can also use the ratio of marginal impacts, which is appropriate if one seeks to maximize welfare.

The appropriate trade-off between greenhouse gases in a cost-benefit analysis was recognized in the early 1990s (Eckaus 1992;Michaelis 1992;Schmalensee 1993) and shortly thereafter a number of papers sought to quantify these ratios (Fankhauser 1995;Hammitt et al. 1996;Kandlikar 1995;Kandlikar 1996;Reilly and Richards 1993;Wallis and Lucas 1994), which were dubbed the "global damage potential". It is the relative global marginal damage potential of greenhouse gas *i* with respect to the marginal damage of carbon dioxide. 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.

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_2 emissions and a dearth of non-CO_2 GHG emission reduction cost estimates, decision-makers have opted to use CO_2 equivalents based on global warming potentials (US EPA, 2008a, 2008b) or, more recently, not value changes in non-CO_2 GHG emissions at all (US Government, 2010). This paper should help inform this issue.

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

2. The model

This paper uses 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.[1] The centuries after the 21st 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 concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model (Hammitt et al. 1992;Maier-Reimer and Hasselmann 1987). The model also contains sulphur emissions (Tol 2006).

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[1] 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.

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 a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°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 global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 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).

People can die prematurely due to climate change, or they can migrate because of 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 2005 and 2014.[2] Differences in impacts were calculated, discounted back to the current year, and normalised by the difference in emissions.[3] 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:

$$SCC_{r,i} = \sum_{t=2005}^{3000} \frac{D_{t,r}\left(\sum_{s=1950}^{t-1} E_s + \delta_s\right) - D_{t,r}\left(\sum_{s=1950}^{t-1} E_{s,i}\right)}{\prod_{s=2005}^{t} 1+\rho+\eta g_{s,r}} \Bigg/ \sum_{t=2005}^{2014} \delta_t \qquad (1)$$

where

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

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

[3] We abstained from levelizing the incremental impacts within the period 2005–2014 because the numerical effect of this correction is minimal while it is hard to explain.

- E are emissions of greenhouse gas i (in metric tonnes of i);
- δ are additional emissions (in metric tonnes of i);
- 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 SCC_i per region, and then aggregate, as follows

$$SCC_i = \sum_{r=1}^{16} \left(\frac{Y_{2005,ref}}{Y_{2005,r}} \right)^{\varepsilon} SCC_{r,i} \tag{2}$$

where

- SCC_i is the global social cost of greenhouse gas i (in US dollar per tonne of i);
- $SCC_{r,i}$ is the regional social cost of greenhouse gas i (in US dollar 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 dollar 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 dollar 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 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

$$GDP_i = \frac{SCC_i}{SCC_{CO2}} \tag{3}$$

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 dollar per tonne of i); and
- i denotes greenhouse gas.

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.

$$GDP_i = \frac{SCC_i}{SCC_{CO2}} =: \frac{SCC_i}{SCC_{CO2}^{cc} + SCC_{CO2}^{fert}} =: \frac{f_i(\vartheta,\varphi)}{f_{CO2}(\vartheta,\varphi) + g_{CO2}(\vartheta,\psi)} \tag{4}$$

Equation (4) is just a change in notation compared to Equation (3). However, it highlights 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

Figure 1 shows the social costs of carbon dioxide. The base case estimate is \$30/tC. This number depends on a large number of assumptions. It is reasonably low because of the positive effects of carbon dioxide fertilization on agriculture. If we turn that off, the social cost rises to \$52/tC. The carbon dioxide fertilization effect is so large because it occurs in the near future. 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 \$25/tC. The effect is relatively small because it occurs in the distant future. 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 a climate sensitivity of 2.0°C (4.5°C) instead, the social cost falls (rises) to \$11/tC (\$65/tC). In the base case, the pure rate of time preference is 1% per year. If we use a pure rate of time preference of 0.1% (3%) per year instead, the social cost rises (falls) to \$186/tC (\$1/tC). The base case does not use equity weights. If we use world-average equity weights instead, the social cost rises to \$91/tC. If we use US (sub-Saharan African) equity weights, the social cost rises (falls) to \$563/tC (\$9/tC). The base case scenario use population, income, and emissions according to the FUND scenario. If we use the SRES scenarios instead, the social cost is \$8/tC (B1), \$12/tC (A1B), \$29/tC (B2) or \$45/tC (A2) using the base case assumptions otherwise.

Figure 2 shows the social cost of methane emissions. In the base case, the estimate is \$205/tCH_4. Qualitatively, the pattern is the same as in Figure 1. This is as one would expect. 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. Note that the social cost of methane is slightly higher without carbon dioxide fertilization than with. The reason is that the impacts of climate change feedback on the growth rates of population and income. Without carbon dioxide fertilization, 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, emitting an additional tonne of methane does 25 times as much damage as emitting an additional tonne of carbon dioxide. Without carbon dioxide fertilization, carbon dioxide is a lot more damaging and methane only a little 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. 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. The global damage potential falls (rises) to 19 (40) as the climate sensitivity rises (falls) to 4.5°C (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 (rises) to 9 (221) as the pure rate of time preference falls (rises) to 0.1%/yr (3.0%/yr). Again, this is amplified by carbon dioxide fertilization. Poor countries contribute less to the marginal impact during the short life-time of methane than during the long life-time of carbon dioxide. Equity weighting is therefore more important for carbon dioxide, and the global damage potential falls to 22. 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 for the social cost of carbon dioxide. The global damage potential therefore varies considerably between scenarios, ranging between 20 (A2) and 55 (B1). 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 is 16, with a range of 7 to 25. The base estimate is the 57th percentile of previous estimates. This estimate therefore corresponds well with earlier work which ignored carbon dioxide fertilization. However, with carbon dioxide fertilization, the base estimate is 25, with a range of 8 to 221. The base estimate is at the 82nd percentile – on the high side (for good reason) but not an outlier. The latest IPCC 100-year global warming potential estimate is 25 (Forster et al. 2007), and the official UNFCCC estimate is 21 (Schimel et al. 1996). This is comparable to our base estimate of the global damage potential, but high relative to 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. Without carbon dioxide fertilization, the global damage potential is lower than the global warming potential because additional warming in the short-term is not as bad as additional warming in the long-run.

Figure 5 shows the social cost of nitrous oxide emissions. In the base case, the estimate is \$5,900/tN_2O. Qualitatively, the pattern is the same as in Figures 1 and 2. However, the social cost of nitrous oxide is more sensitive than the social cost of methane to the pure rate of time preference, the climate sensitivity and the emissions/socioeconomic scenario because of the longer atmospheric lifetime of nitrous oxide.

Figure 6 shows the global damage potential of nitrous oxide. It is 437 in the base case. Without carbon dioxide fertilization, it rises to 713. Without the climate change feedback on the terrestrial carbon cycle, the global damage potential falls slightly to 422. As with methane, the global damage potential falls (rises) to 436 (438) as the climate sensitivity rises (falls) to 4.5°C (2.0°C). The marginal impact of nitrous oxide and carbon dioxide (without carbon dioxide fertilization) respond in the same way to the climate sensitivity. The global damage potential falls to 367 (394) as the pure rate of time preference falls (rises) to 0.1%/yr (3.0%/yr). The global damage potential is highest for the middle pure rate of time preference without carbon dioxide fertilization, as carbon dioxide is more effective 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. As with methane, the global damage potential falls with equity weighting, but only slightly: 437.3 to 436.8. The global damage potential varies between scenarios, ranging from 426 (A2) to 383 (B1).

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 450 to 680. This 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 increases 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. The global warming potential assumes constant concentrations, while the global damage potential assumes rising concentrations. Under rising concentrations, nitrous oxide is more important. Furthermore, discounting reduces the importance of impacts in the long run, when carbon dioxide dominates nitrous oxide.

The difference with earlier estimates of the global damage potential is explained as follows. The incremental radiative forcing of nitrous oxide relative to carbon dioxide starts high and rises for some 30 years, after which it continuously falls. 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. This means that impacts in the medium-term are more important, and nitrous oxide is at is most potent in the medium term.

Figure 8 shows the social cost of sulphur hexafluoride emissions, one of the more prominent of the high-GWP gases. In the base case, the estimate is \$543,000/tSF_4. Qualitatively, the pattern is similar to that in Figures 1, 2 and 4. Responsiveness is similar to the social cost of nitrous oxide, except the social cost of sulphur hexafluoride is more responsive to the pure rate of time preference due to its much long atmospheric lifetime of 3200 years (compared to 114 for nitrous oxide and 12 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. With the climate change feedback on the terrestrial carbon cycle, the global damage potential falls slightly to 36,700. As with methane and nitrous oxide, the global damage potential rises (falls) to 42,500 (36,900) as the climate sensitivity rises (falls) to 4.5°C (2.0°C). The global damage potential rises with the climate sensitivity, reflecting the long atmospheric life-time of sulphur hexafluoride. The global damage potential rises to 70,500 (23,400) as the pure rate of time preference falls (rises) to 0.1%/yr (3.0%/yr). This reflects the long life time of sulphur hexafluoride. Unlike with methane, the global damage potential rises (to 38,700) with equity weighting – the reason is the same: equity weighting emphasizes impacts in the long run and hence long-lived gases. The global damage potential varies between scenarios, ranging from 44,100 (A2) to 30,100 (B1). Carbon dioxide fertilization again enhances the differences between the scenarios.

There is only one other estimate of the global damage potential. (Hope 2006) puts it at 38,600, very close to our estimate (without carbon dioxide fertilization). This compares to the latest IPCC 100-year global warming potential of 22,800 (Forster et al. 2007), and UNFCCC official value of 23,900 (Schimel et al. 1996). Figure 8 shows that the global damage potential falls with emissions/socioeconomic scenario. The difference between the global warming potential and global damage potential is 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. This, rather than global warming potentials, is the appropriate trade-off between greenhouse gases in a cost-benefit analysis. We do this for a range of scenarios and parameter specifications. We find that the social cost of carbon dioxide is $30/tC in 2010 for a pure rate of time preference of 1%. This is well in line with previous estimates (Tol 2009). The model we use for the analysis, *FUND*, includes the positive effects of carbon dioxide fertilization on agriculture and forestry. This substantially reduces the social cost of carbon dioxide while the social costs of the other greenhouse gases are hardly affected. As a result, our estimates of the global damage potentials are substantially higher than previous estimates. 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 incremental impacts are less important in the short run. However, our sensitivity results reveal that changes in methane become more important in terms of marginal impacts under lower emissions and less vulnerable conditions. The global damage potential of sulphur hexafluoride is high compared to its global warming potential because the former is evaluated against rising concentrations and the latter against constant concentrations. 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. Overall, the results presented here suggest that, based on the marginal benefits of emissions reductions, climate policy should put more emphasis on abatement of the non-carbon dioxide greenhouse gases than previously thought.

There are a number of caveats to these results. The conclusions are based on a single model and a limited set of sensitivity analyses. We consider only three non-CO_2 greenhouse gases. More importantly, we omit uncertainty from the analysis. Because part of carbon dioxide stays in the atmosphere practically forever, irreversibility may well put a premium on carbon dioxide emission reduction. Similarly, the model omits ocean acidification, another reason to favour carbon dioxide abatement over reducing other greenhouse gases. These matters are deferred to future research.

Acknowledgements

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Figures

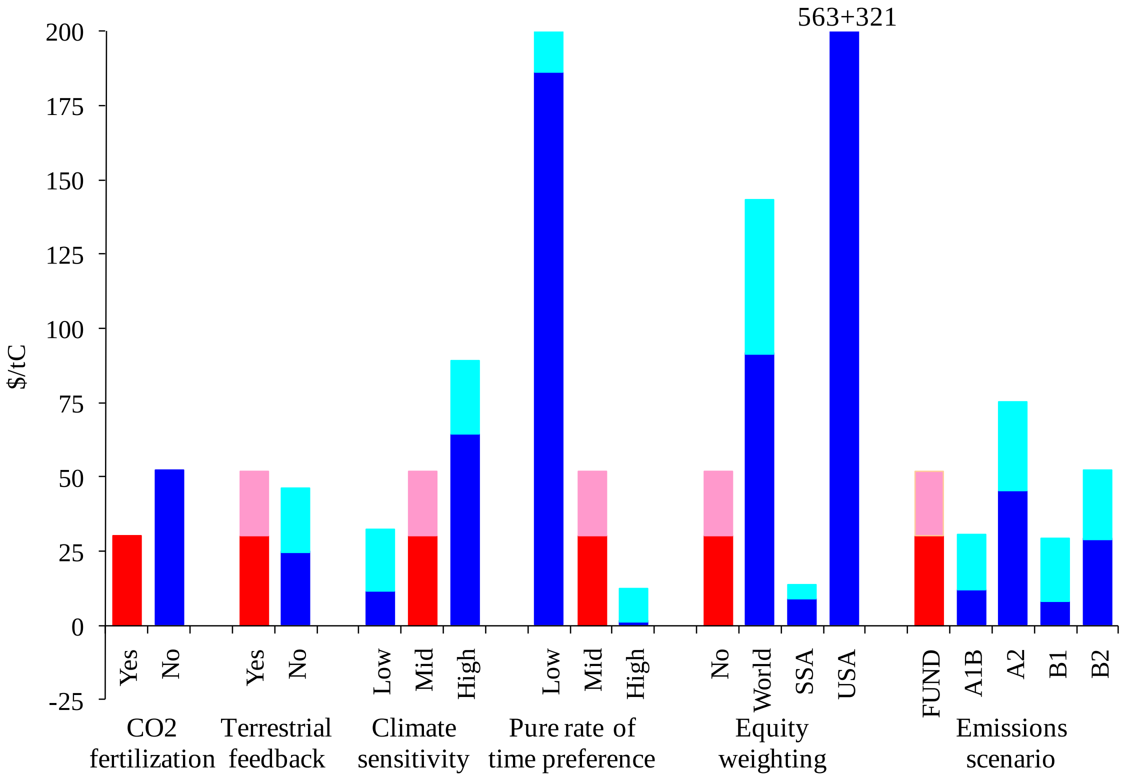


Figure 1. The social cost of carbon dioxide emissions. Red denotes the estimate with our base assumptions. The darker colours are with carbon dioxide fertilization, the lighter colours are the differences with and without carbon dioxide fertilization.

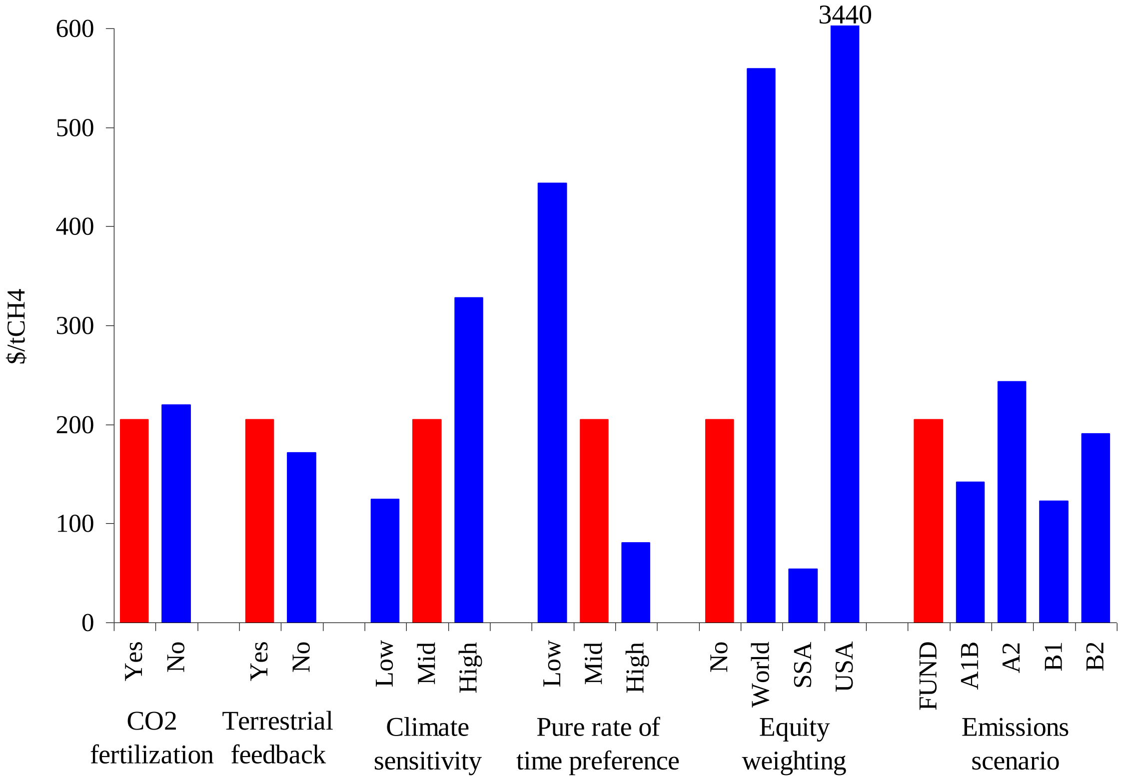
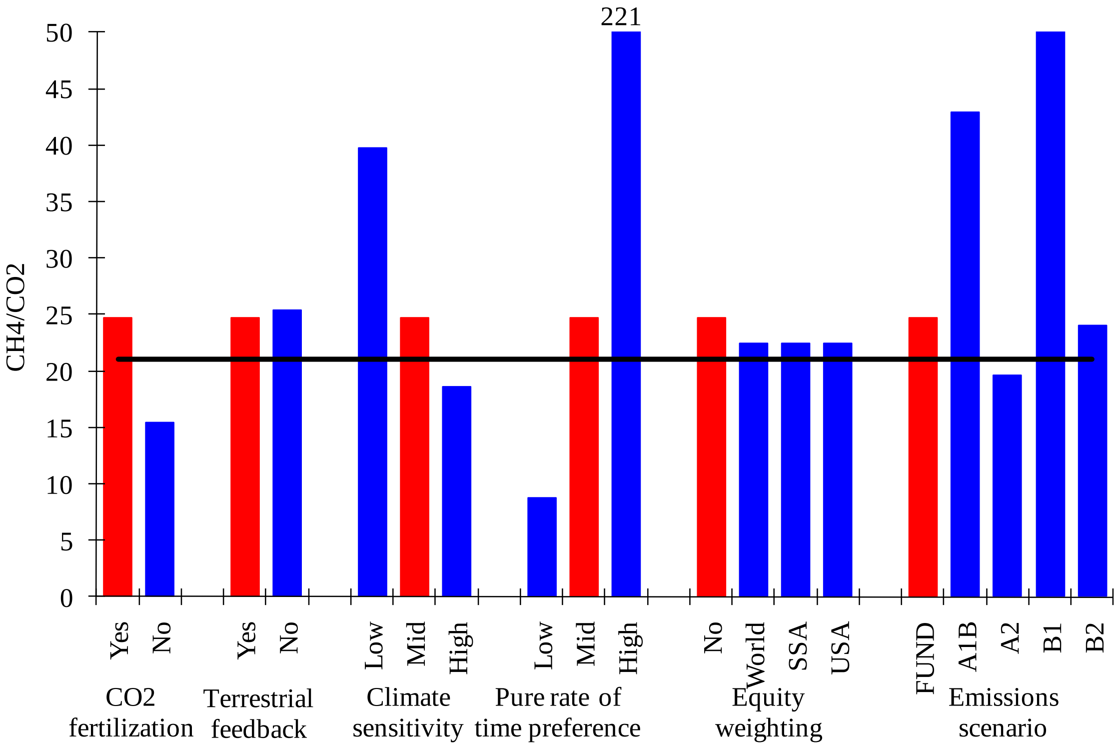


Figure 2. The social costs of methane emissions. Red denotes the estimate with our base assumptions.



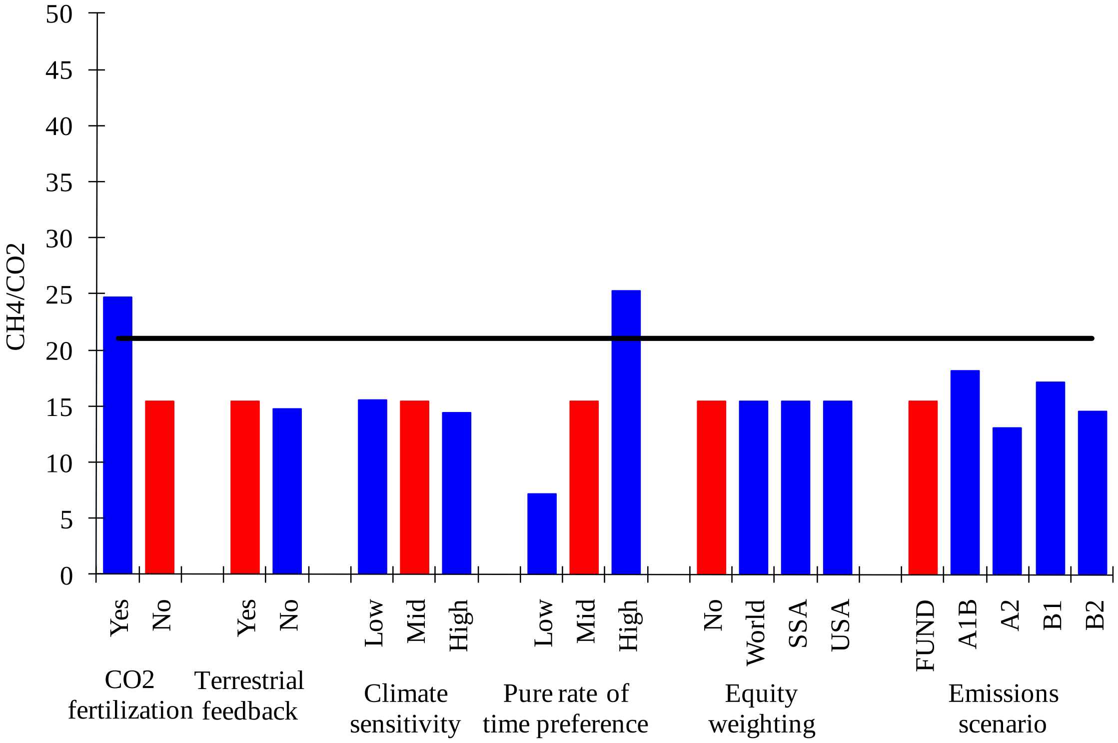


Figure 3. The global damage potential of methane; for comparison, the global warming potential is shown as well (straight line); top panel: carbon dioxide fertilization; bottom panel: no carbon dioxide fertilization.

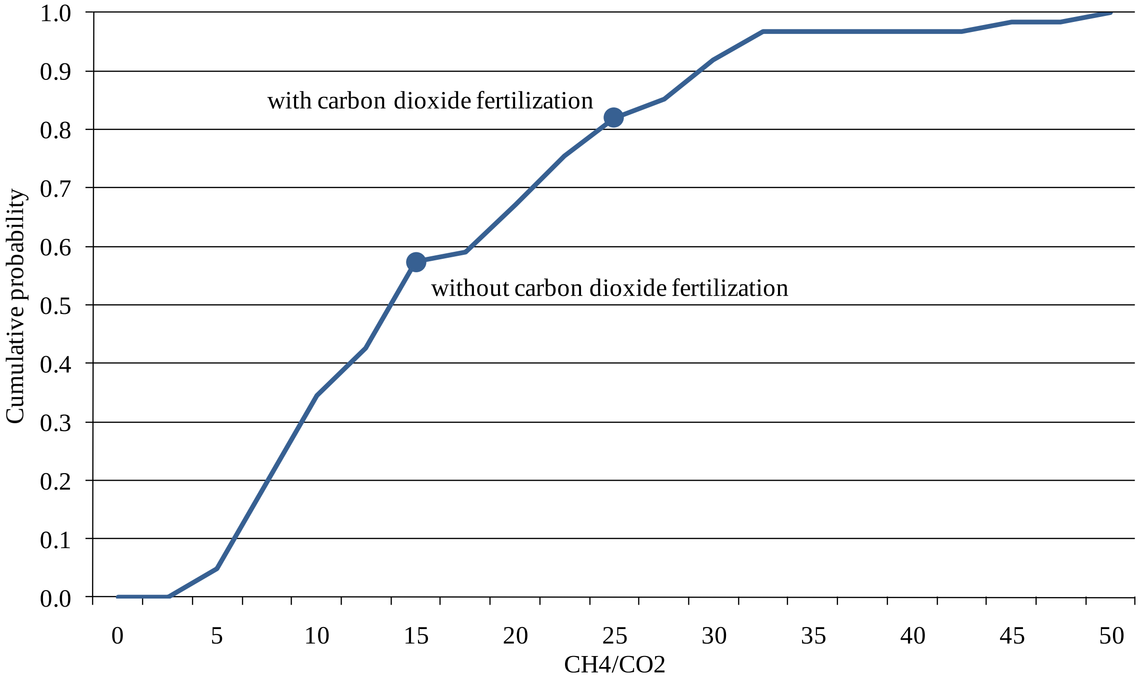


Figure 4. Our base estimates of the global damage potential of methane (dots) compared to previous estimates (cumulative density function).

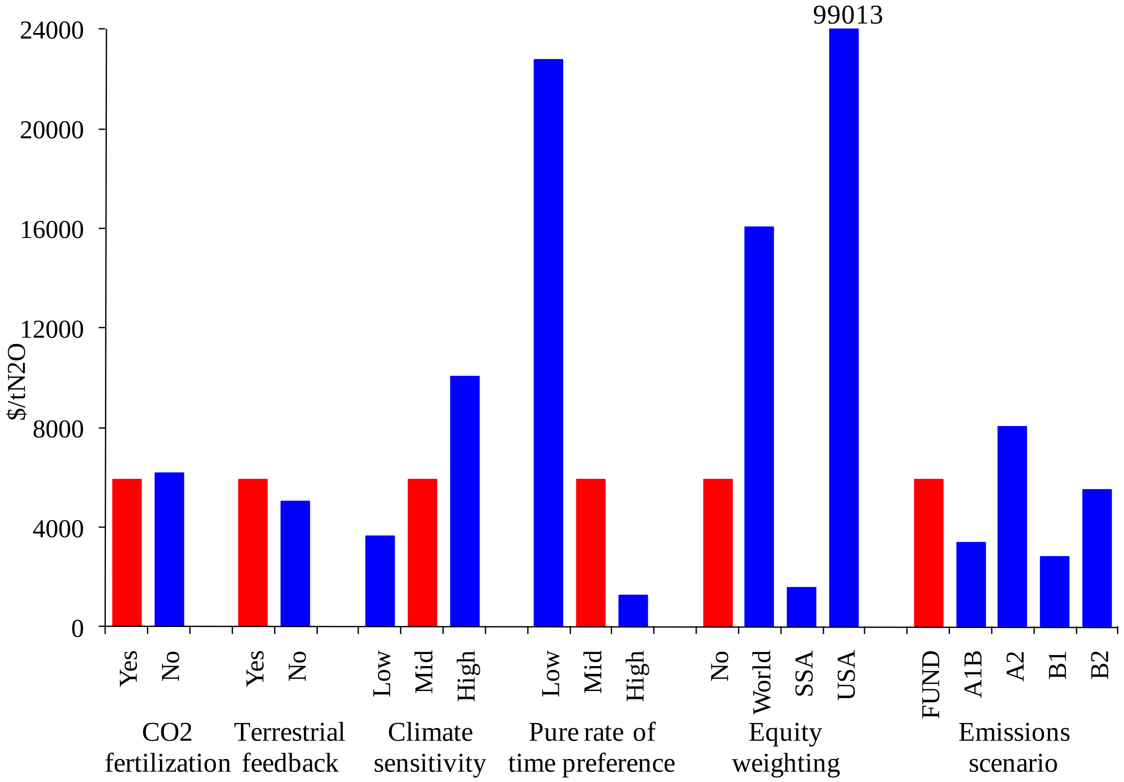


Figure 5. The social cost of nitrous oxide emissions. Red denotes the estimate with our base assumptions.

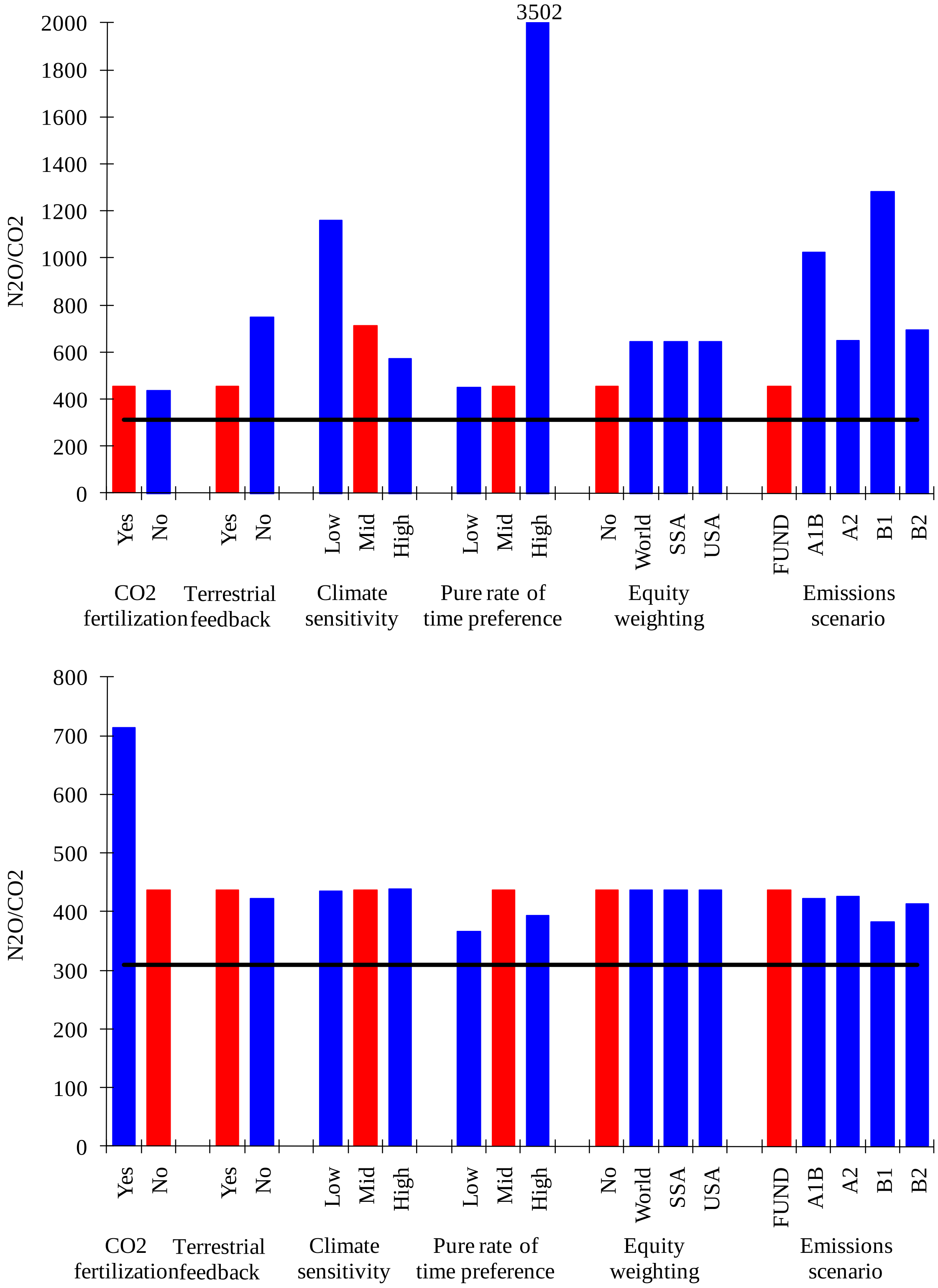


Figure 6. The global damage potential of nitrous oxide; for comparison, the global warming potential is shown as well (straight line); top panel: carbon dioxide fertilization; bottom panel: no carbon dioxide fertilization.

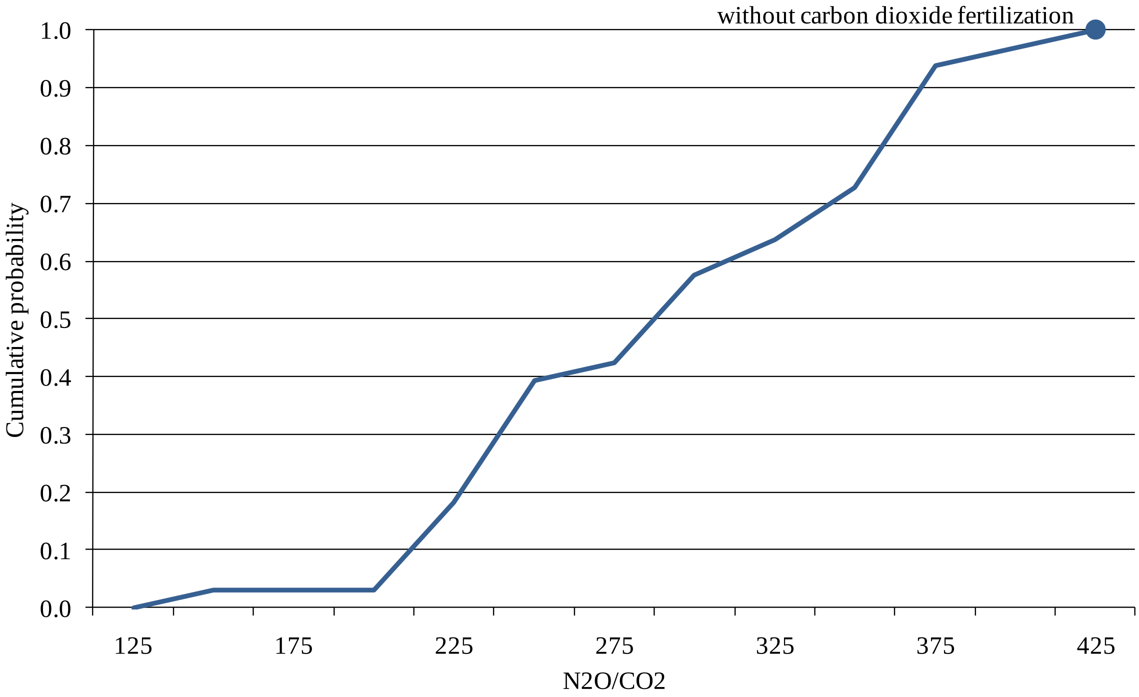


Figure 7. Our estimate of the global damage potential of nitrous oxide (vertical line) compared to previous estimates (cumulative density function).

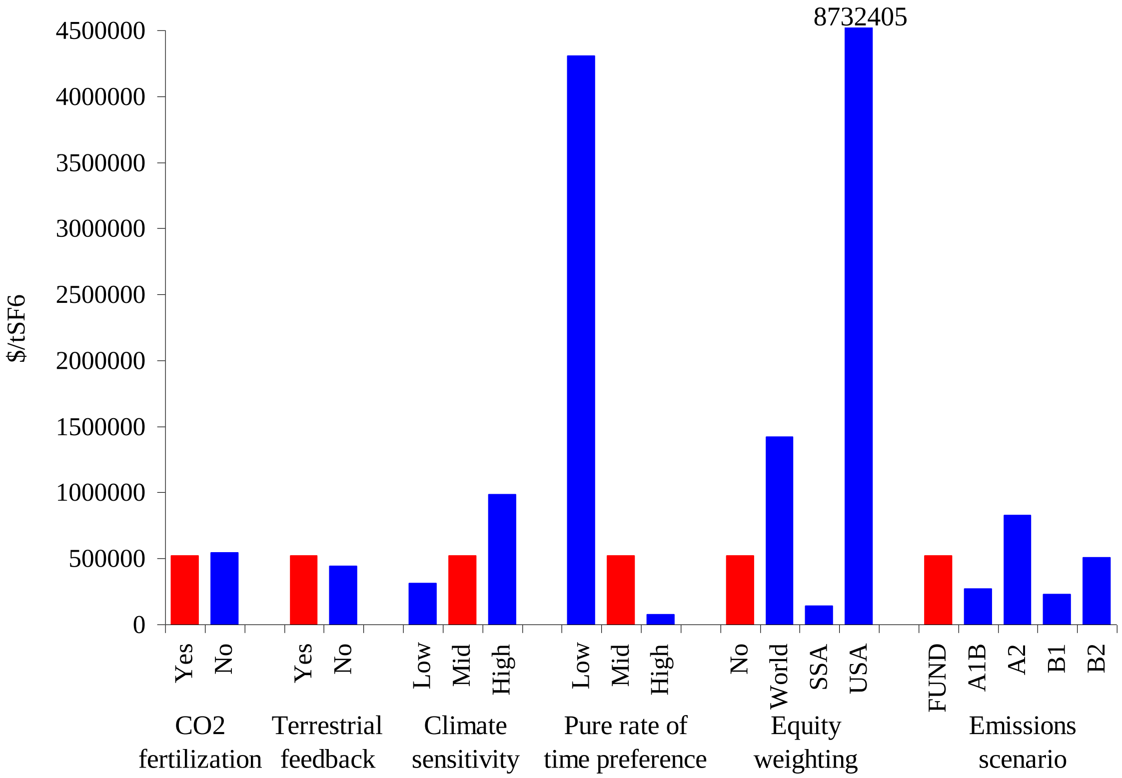


Figure 8. The social costs of sulphurhexafluoride emissions. Red denotes the estimate with our base assumptions.

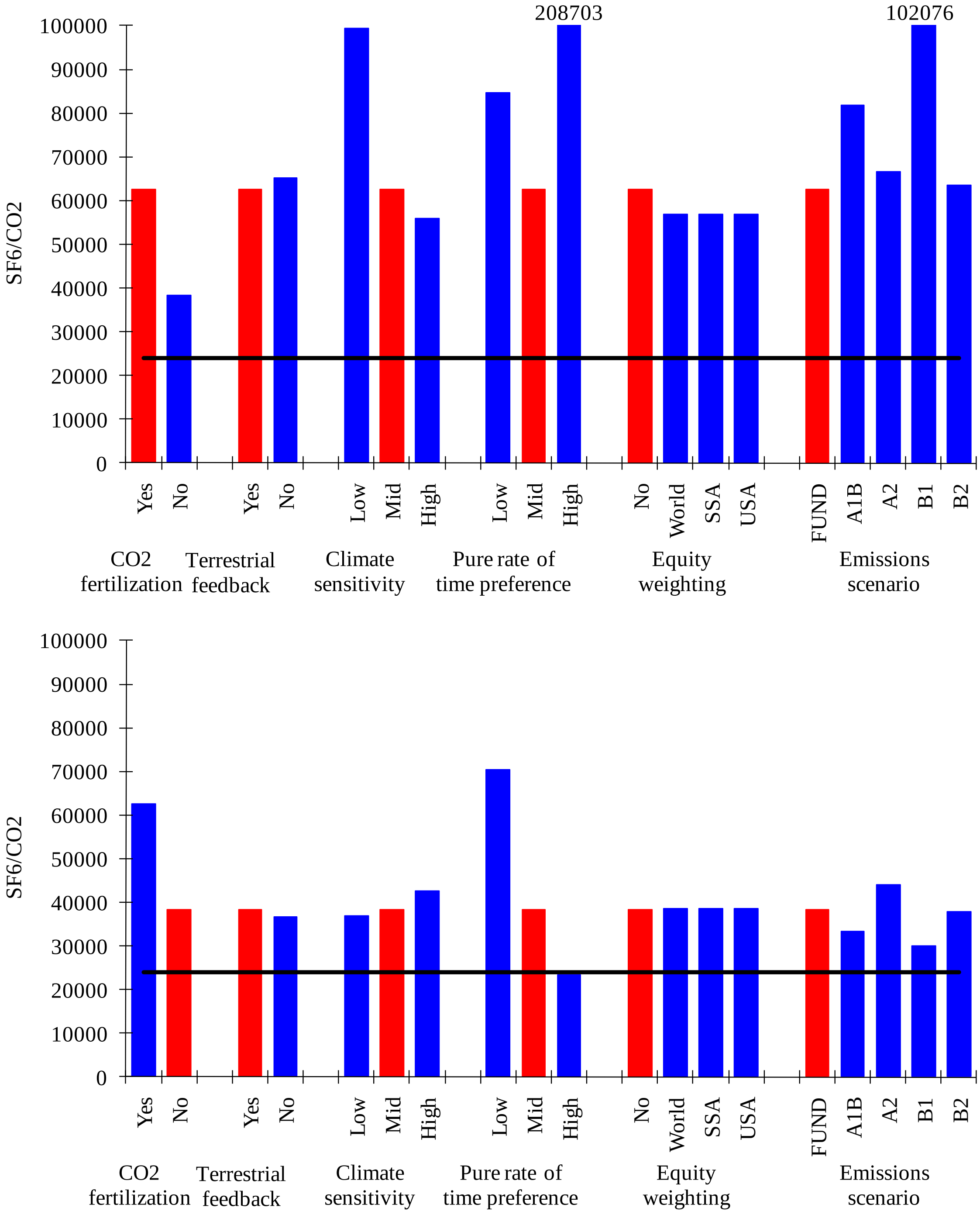


Figure 9. The global damage potential of sulphurhexafluoride; for comparison the global warming potential is shown as well (straight line); top panel: carbon dioxide fertilization; bottom panel: no carbon dioxide fertilization.

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