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A Perspective Paper on Methane Mitigation as a Response to Climate Change

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David Anthoff

Economic and Social Research Institute, Dublin, Ireland
david.anthoff@esri.ie, http://www.david-anthoff.de

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Copenhagen Consensus Center
Copenhagen Business School
Solbjerg Plads 3
DK-2000 Frederiksberg
Denmark

+45 3815 2255
info.ccc@cbs.dk
www.copenhagenconsensus.com

PREFACE

ABSTRACT

A methane emission mitigation policy that follows the spending schedule suggested by the Copenhagen Consensus project does not pass a benefit-cost test. More reasonable methane mitigation policies spend less on mitigation in the years 2010-20 than suggested by the Copenhagen Consensus project, but more in later time periods. Such policies can generate significant net benefits. At the same time, they are no substitutes for CO2 emission mitigation policies because they do not alter the long term temperature trend beyond marginal perturbations. Joint methane and CO2 emission mitigation is an optimal policy mix and leads to highest net benefits, suggesting that a "either-or" approach between CO2 or methane emission mitigation is misguided.

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The Copenhagen Consensus Center has commissioned 21 papers to examine the costs and benefits of different solutions to global warming. The project's goal is to answer the question:

"If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?"

The series of papers is divided into Assessment Papers and Perspective Papers. Each Assessment Paper outlines the costs and benefits of one way to respond to global warming. Each Perspective Paper reviews the assumptions and analyses made within an Assessment Paper.

It is hoped that, as a body of work, this research will provide a foundation for an informed debate about the best way to respond to this threat.

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CONTENTS

INTRODUCTION

Kemfert and Schill (2009) provide a thorough overview of the details of methane emission mitigation options and relevant recent work on estimating costs of methane emission mitigation. Their estimates of benefits of mitigation of CH4 are less convincing: they use global warming potential (GWP) conversion rates to calculate equivalent emission reductions in terms of CO2 and then use published estimates of the social cost of carbon to arrive at monetized benefit estimates of methane mitigation. Using GWP conversion rates is widely believed to be flawed in economic assessments of climate change (c.f. Manne and Richels 2001) and the benefits estimated by Kemfert and Schill (2009) suffer from this weakness as well. Finally, the two solutions ("portfolios") proposed are difficult to compare with any of the other solutions in the Copenhagen Consensus project for two main reasons: First, the cost estimates are limited to just one year (2020) and do not seem to be discounted into net present value terms. Second, the benefit-cost ratios calculated in the assessment paper are an inappropriate measure to rank solutions because costs (or, alternatively, benefits) are not held constant across solutions. This also prevents comparison of benefit-cost ratios with solutions from other solution categories. Net benefit estimates (which would be the appropriate measure to rank solutions when neither costs nor benefits are fixed across solutions) are not provided in the assessment paper.

I provide alternative estimates of benefits and costs of methane emission reductions in this perspective paper. I use the integrated assessment model FUND to calculate both benefits and costs of three different mitigation solutions for methane emissions and investigate their relationship with CO2 mitigation options.

In estimating benefits of methane emissions I do not rely on global warming potential conversion factors but rather employ a reduced form model of the methane cycle and calculate changes in radiative forcing due to perturbations of the methane stock in the atmosphere. This approach properly takes into account the very different atmospheric lifetime of methane compared to other greenhouse gases and can for example account properly for the fact that methane emission reductions that are limited to, say, the next ten years (like suggested by the Copenhagen Consensus guidelines) will have no effect on the climate in the long run.

Further, I follow the discounting guidelines of the Copenhagen Consensus project and discount all benefits and costs consistently with 6% and 3% per year. While this approach does not reflect best practice as found in the literature in my opinion, it does allow for a meaningful comparison of benefits and costs with estimates from other solution categories.

Finally, I follow the spending suggestion of the Copenhagen Consensus project of 250 billion dollar per year for ten years in one of my solutions. The benefit-cost ratio of that solution can be compared in a meaningful way with benefit-cost ratios from other solution categories where the same amount of money is spent. My other solutions do not follow this spending schedule: I solve for optimal mitigation paths without constraints in which decade money has to be spent and contrast this with solutions that conform with the Copenhagen Consensus spending schedule. I calculate net benefits for all solutions, making comparison across solutions feasible.

SOLUTIONS

All benefits and costs are calculated with version 3.5 of the integrated assessment model FUND. A full documentation of FUND can be found at http://www.fund-model.org, a brief description is contained in the appendix. The methane mitigation cost functions are described in Tol (2006). All dollar figures are in 1995 USD price levels. Numbers in tables are in billion USD.

In solution A I try to roughly follow the spending schedule suggested by the Copenhagen Consensus project. The schedule is outlined as spending 250 billion US dollar per year for a time period of ten years. The net present value of that expenditure is roughly 2 trillion US dollars with a discount rate of 6%. I then search for a tax rate on methane emissions in the FUND model at which the net present value of methane mitigation costs equals 2 trillion US dollars.

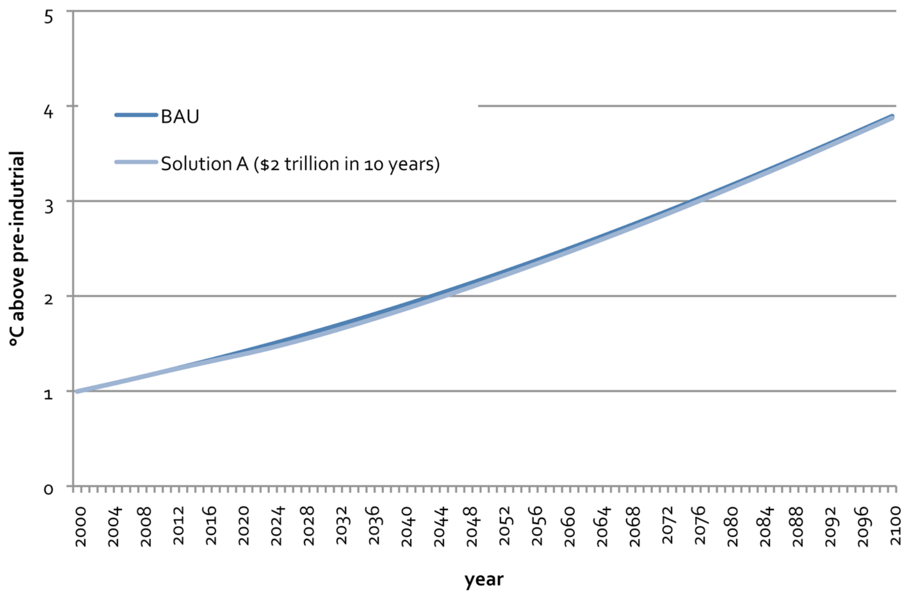
Costs and benefits for this solution are presented in Table 1. Costs are much higher than benefits for both discount rates. The reason for this is easily explained: in order to spend so much on methane mitigation, methane emissions would have to be eliminated almost completely during those ten years in the FUND model. Emission levels would be reduced to between 1% and 4% of today's emission levels. The results for this solution are highly speculative: The cost function for methane emission reduction is simply an extrapolation for such high emission reductions and overall a solution that would imply such radical emission reductions seems to be quite unrealistic.

There are two relevant results from this solution nevertheless: First, spending the equivalent of 2 trillion US dollars just on methane emission reductions in just the next ten years probably belongs in the realm of fiction, and certainly does not pass a benefit-cost test. Second, even such a strong mitigation of methane emissions in the short run has literally no effect on the long run temperature projection. Figure 1 plots temperature above pre-industrial in degree Celsius as projected by FUND for a business as usual scenario with no climate policy and the temperature projection for solution A. While there is a small reduction in temperatures right after the ten year emission reduction of methane in the next decade, there is no long lasting effect of such a policy. This comes as no surprise: the atmospheric lifetime of methane is much smaller than that of CO_2, and any effects of a policy that is restricted to just the next ten years will be gone by about mid-century. This is one of the key differences between a methane and a CO_2 policy: the effects of methane mitigations are limited to a much shorter time span (about ten years), while CO_2 policy has effects in the long run, due to the longer lifetime of CO_2 in the atmosphere.

Table 1: Benefits and Costs of solution A

Solution A ($2 trillion in 10 years)		
Benefit and Costs	Discount Rate	
	Low (3%)	High (6%)
Benefit	$1,179	$365
Cost	$2,126	$2,081

Figure 1: Temperature for BAU and solution A



Does this result imply that methane mitigation is not a worthwhile option? In order to investigate this question I now look for proper optimal mitigation paths (solution C) that are not restricted by an arbitrary spending schedule that might in itself rule out the best solution for methane mitigation. In doing so, I make a comparison with other solution categories in the Copenhagen Consensus difficult: If they restrict themselves to the spending schedule of the Copenhagen Consensus project as well, one would have to compare apples and oranges, namely, an optimal methane mitigation solution presented in this paper to, e.g., a CO2 mitigation solution that is restricted by the spending schedule of the Copenhagen Consensus project (and therefore almost certainly not a true optimal CO2 mitigation solution). I therefore also compute an optimal CO2 mitigation solution (solution B) in order to allow a proper comparison of net benefits of methane vs. CO2 mitigation options. I then finally compute the optimal joint mitigation path, in which both CO2 and methane emissions are regulated in an optimal fashion and compute net benefits for that solution (solution D).

Benefits and costs for those three solutions for two discount rates are presented in Tables 2, 3 and 4. Table 5 presents net benefits for all solutions, the relevant measure to compare solutions that differ with respect to costs.

The first observation to make is that all solutions except for the one restricted by the Copenhagen Consensus spending schedule produce net benefits, and that in particular methane emission reduction solutions can produce significant net benefits if not restricted to spending enormous amounts of money in just the next ten years.

The second observation is that net benefits for a joint solution that both mitigates CO2 as well as methane emissions at the same time is always ranked highest in terms of net benefits, neither a CO2 or methane only solution can achieve similar net benefits.

The third observation is that the ranking of a CO2 or methane emission only solution depends on the discount rate. With a discount rate of 6% a methane emission only solution yields higher net benefits than a CO2 emission solution, while with a 3% discount rate the opposite holds. The explanation for this result lies in the interaction of the discount rate and the atmospheric lifetime of the two gases. Methane emissions stay in the atmosphere relatively shortly (for about 10 years), while CO2 has an atmospheric lifetime that is much longer. The benefit of reducing emissions of either gas is defined as the avoided damage from that emission reduction. The total damage caused by an emission at a specific point in time is the sum of damages caused by this emission in the future. With methane emissions, those damages are all concentrated in a relatively short time frame after the emission, they will occur only in roughly the ten years after the initial emission of methane, given the short atmospheric lifetime of CH4. The damages from a specific CO2 emission are spread out over a much longer time frame, namely the atmospheric lifetime of CO2, which amounts to many centuries. A change in discount rate therefore changes damage estimates of methane emissions much less than damage estimates of CO2 emissions. In fact, with a discount rate of 6%, the climate problem is simply not addressed in a significant way in either solution: For a methane only reduction solution temperature is marginally changed along the business as usual path (and this is highly profitable) and for a CO2 only reduction solution climate change is also not addressed in any comprehensive way, because most impacts from climate change are discounted away. I conclude from this that with a discount rate of 6%, climate change is simply not valued as an urgent problem in the first place. In such a situation, high net benefits can be gained by reducing methane emissions, but those emission reductions occur at the margin and do not alter the general temperature trend. With a discount rate of 3%, a methane emission reduction strategy can again be highly profitable, but again this will be gained by marginally changing the temperature along the business as usual path.

Table 2: Benefits and Costs of solution B

Solution B (Optimal C tax)		
Benefit and Costs	Discount Rate	
	Low (3%)	High (6%)
Benefit	$19,015	$93
Cost	$12,376	$20

Table 3: Benefits and Costs of solution C

Solution C (Optimal CH4 tax)		
Benefit and Costs	Discount Rate	
	Low (3%)	High (6%)
Benefit	$8,818	$295
Cost	$3,718	$134

Table 4: Benefits and Costs of solution D

Solution D (Optimal joint taxes)		
Benefit and Costs	Discount Rate	
	Low (3%)	High (6%)
Benefit	$24,511	$375
Cost	$13,976	$148

Table 5: Net benefits

Net Benefits	Discount rate	
	Low (3%)	High (6%)
Solution A ($2 trillion in 10 years)	-$947	-$1,715
Solution B (Optimal C tax)	$6,639	$73
Solution C (Optimal CH4 tax)	$5,100	$162
Solution D (Optimal joint taxes)	$10,534	$227

Figure 2: Temperature

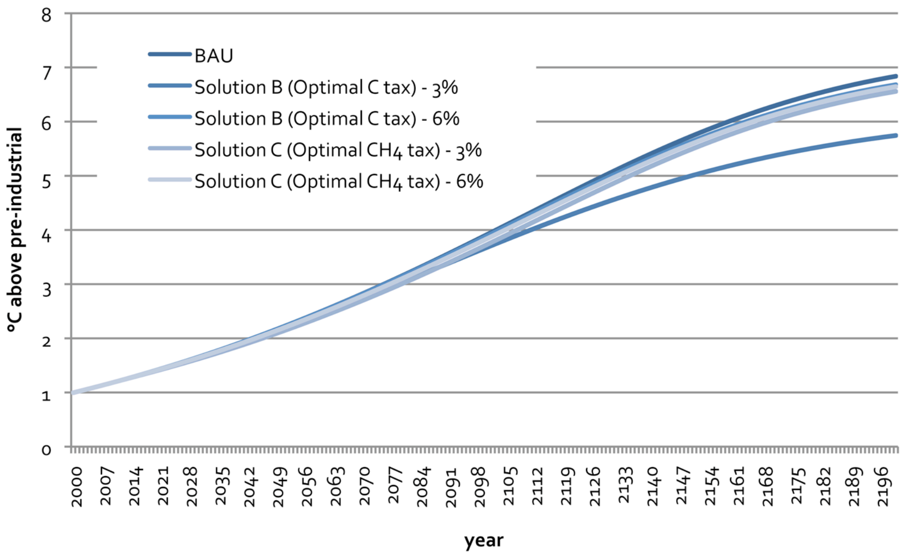


Table 6: Costs in 2010-2019

NPV Cost in 2010-2019	Discount rate	
	Low (3%)	High (6%)
Solution A ($2 trillion in 10 years)	$2,126.39	$2,080.54
Solution B (Optimal C tax)	$58.76	$0.01
Solution C (Optimal CH4 tax)	$267.04	$21.24
Solution D (Optimal joint taxes)	$268.87	$21.02

I will now compare the three optimal solutions B-D with the solution A that confirms with the Copenhagen Consensus project. Table 6 shows the net present value of total expenditures on mitigation of either methane or CO2 in the time period 2010-19. The striking result here is that none of the optimal policies come even close to spending as much as the solution that conforms with the Copenhagen Consensus spending suggestion in the first decade. At the same time total (i.e. not limited to 2010-19) expenditures of the optimal solutions B-D for a discount rate of 3% are much higher than what is spent in solution A. With a discount rate of 3%, this suggests that while expenditures of much more than 2 trillion US dollar in net present value terms are optimal, a large fraction of that should be spent after 2020. For a discount rate of 6% the total expenditure suggested by the Copenhagen Consensus project is overall too large. These results confirm an earlier suspicion: The spending suggestion of the Copenhagen Consensus itself is far away from an optimal response to climate change.

LIMITATIONS

In this section I will outline limitations both of the assessment paper as well as of the results in this perspective paper and elaborate how I judge those to affect the applicability of the results for policy advise.

The first limitation concerns the published benefit-cost ratios. The only solution that confirms to the spending schedule suggested by the Copenhagen Consensus project from both the perspective paper as well as this study is solution A in this study. All other solutions spend vastly different sums on mitigation in the different solutions. This makes a ranking by benefit-cost ratios arbitrary. The proper metric to rank solutions in this situation is net benefits, but those are not published for the assessment paper. Table 7 has benefit-cost ratios for the solutions in this paper, and a comparison to the corresponding net benefits in Table 5 shows clearly that a ranking by benefit-costs ratios would be misguided.

The second limitation is specific to the assessment paper by Kemfert and Schill, but again makes comparison with solutions from other solution categories almost impossible. The assessment paper only looks at mitigation costs in *one* year, namely 2020. Those costs do not seem to be discounted into net present value equivalents. Benefits are calculated by using the dubious global warming potential concept and thereby certainly misrepresent the specific dynamics of methane stocks in the atmosphere. In summary, those two limitations make comparison with net benefits from other solution categories highly unconvincing.

The third limitation concerns numerical results in this study. All estimates in this paper are calculated by using a deterministic version of the FUND model. In such a mode the model uses best guess values for all input parameters and this study does not take into account any uncertainties surrounding climate change projections. This is clearly sub-standard, many previous studies have shown that taking proper account of uncertainty can have a significant effect on quantitative results from integrated assessment models (e.g. Stern 2007; Anthoff, Tol et al. 2009; Anthoff, Tol et al. 2009). The reason I have not incorporated uncertainty into this study is purely a technical one: Such studies take considerable amount of computational time and could not be fitted into the tight time frame of the Copenhagen Consensus project. This limitation does mean that while most of the qualitative conclusions are sound, the precise quantitative magnitudes are not appropriate input into policy design. In particular, earlier studies suggest that incorporating uncertainty into the analysis would produce more aggressive emission mitigation paths for an optimal policy. The assessment paper also suffers from not account for uncertainty.

Table 7: B/C ratios

B/C ratios	Discount rate	
	Low (3%)	High (6%)
Solution A ($2 trillion in 10 years)	0.6	0.2
Solution B (Optimal C tax)	1.5	4.7
Solution C (Optimal CH4 tax)	2.4	2.2
Solution D (Optimal joint taxes)	1.8	2.5

The final limitation concerns the discounting schemes employed in the Copenhagen Consensus project. A 6% constant consumption discount rate in particular seems highly inappropriate and not within the range of discount rates commonly employed in economic climate change analysis. In almost all integrated assessment models, the standard approach to discounting is to specify a pure rate of time preference, and then calculate the interest rate as an endogenous variable as a function of the time preference rate, the per capita consumption rate and the elasticity of marginal utility, using what is commonly referred to as the Ramsey equation (e.g. Nordhaus and Boyer 2000; Guo, Hepburn et al. 2006; Hope and Newbery 2007; Nordhaus 2008). There is an interesting and legitimate debate regarding how the pure time preference rate and the elasticity of marginal consumption should be chosen. Proponents of the so called "descriptive approach" usually calibrate their models to observed interest rates *today*. Those studies in general are those with the highest discount rates. But even these studies do *not* use consumption discount rates that are as high as 6% over the whole time horizon. Because per capita consumption growth rates fall in all those models in the second half of the century, the consumption interest rates employed by that approach in later years are smaller than in earlier periods. Using a 6% constant consumption discount rate seems clearly higher than what is commonly thought to be studies with high discount rates (e.g. Nordhaus 2008). The discounting schemes also ignore important research about discounting under uncertainty (c.f. Weitzman 1998; Weitzman 2001; Gollier 2004; Gollier and Zeckhauser 2005). All experience from climate change economics suggests that the choice of discount rate and scheme is one of the most important ones a modeler can make. Given that the Copenhagen Consensus project only considers two very basic discounting schemes, it already ignores at its outset what is probably the most relevant discussion in the economics of climate change. The quantitative results presented in this study follow the discounting guidelines of the Copenhagen Consensus project and are thereby not reflecting state of the art as found in the literature, in my opinion.

CONCLUSION

This study looked at the benefits and costs of methane emission reductions. I looked at one solution that conformed to the guidelines given for the Copenhagen Consensus study and contrast it with solutions that are optimal policy responses to the climate change problem. There are five main conclusions from this study.

First, a methane emission reduction solution that follows the spending schedule suggested by the Copenhagen Consensus project does not pass a benefit-cost test. I calculate benefit-cost ratios well below one for such a solution, irrespective of the discount rate used in the assessment (the benefit-cost ratio is 0.6 for a discount rate of 3% and 0.2 for a discount rate of 6%). The specific quantitative results for this solution are extremely unreliable: In order to spend the enormous amounts of money suggested by the Copenhagen Consensus project in just ten years on methane reductions, one would have to reduce methane emissions to between 1% and 4% percent of today's emissions levels, and any cost estimate for that range of emission reductions is highly speculative. The results for this solution say little to nothing about the desirability of methane reductions from a policy point of view, they are mainly a consequence of the highly sub-optimal nature of the spending schedule suggested by the Copenhagen Consensus project.

Second, the spending suggestion of the Copenhagen Consensus project of 250 billion dollar per year for ten years excludes the solutions that create the greatest net benefit. In the optimal mitigation solutions that are not restricted to the spending schedule of the Copenhagen Consensus project, significantly less is spent in the years 2010-2020 than in the solution following the 250 billion dollar per year for ten years setup. At the same time, the total optimal expenditure on mitigation is much larger in net present value terms than the net present value of the high expenditures of the Copenhagen Consensus project in just a few years for a discount rate of 3%. The conclusion from this is simple: In net present value terms, one should spend a lot more than suggested by the Copenhagen Consensus project spending schedule, but that spending should not occur in some arbitrarily set time frame but rather should follow an optimal path over time, which is very different from the one suggested by the Copenhagen Consensus project. For a 6% discount rate, overall optimal spending in net present value terms is always lower than the net present value of the spending schedule of the CC project because with such a high discount rate, climate change is not a problem almost by assumption.

Third, while an optimal methane mitigation strategy is highly profitable at the margin, it does not significantly contribute to solving the climate problem. There are two lines of evidence on which I base this conclusion. The first is simply that with a discount rate of 3%, net benefits of an optimal methane only mitigation strategy are lower than net benefits of a CO2 only mitigation strategy. The second exhibit is a look at the temperature profile for the various solutions. The methane only mitigation strategy does not alter the temperature trajectory in any significant way from the business as usual, while any solution that also includes CO2 emission mitigation does. As discussed above, I ignore key uncertainties in my estimate of benefits of keeping temperatures below the business as usual path in this study. Including such uncertainties would increase net benefit estimates of a solution that changes the temperature trajectory in a significant way (which requires CO2 mitigation) over a solution that reaps high net benefits at the margin, but would not alter the temperature profile (like a methane only mitigation solution).

Fourth, methane mitigation can add significant net benefits when combined with a CO2 mitigation policy. Net benefits for a solution in which both CO2 and methane mitigation are chosen optimally are almost the sum of net benefits of doing either a CO2 or CH4 mitigation only solution, regardless of the discount rate chosen. This strongly suggests that an "either or" view which attempts to judge whether CO2 or CH4 emission mitigation is a better approach to climate change is misguided. The proper solution is a portfolio approach which combines various policy responses. This result also is in line with basic economic theory: if there are multiple significant externalities (like methane emissions and CO2 emissions), an optimal solution should internalize both externalities.

Fifth, the quantitative results in this perspective paper as well as in the primary assessment paper on methane emission reductions suffer from strong limitations that make it difficult to compare them with other solution categories and make them of limited relevance for policy advice. The only solution that confirms with the spending schedule suggested by the Copenhagen Consensus project is solution A in this perspective paper. All other solutions (both in the assessment and perspective paper) spend very different amounts of money on mitigation in net present value terms. A ranking of solutions by benefit-cost ratios therefore would be entirely arbitrary. The proper metric for ranking solutions that differ both in total costs as well as benefits is net benefits. The discounting schemes used for the Copenhagen Consensus project are not state of the art in climate change economics. Almost all integrated assessment models today use an approach where the consumption discount rate is endogenously calculated using the Ramsey equation, thereby reflecting actually per capita consumption growth paths employed in the model. This is particularly relevant for the high discount rate of 6% in the Copenhagen Consensus project: in later (relevant) periods it is even higher than what is commonly assumed to be a high discounting scheme that calibrates interest rates to observed market rates. Finally, neither the assessment paper nor the perspective papers factors uncertainty into the analysis. Previous studies have shown that including uncertainty significantly changes quantitative results (Anthoff, Tol et al. 2009). More recent work started a discussion whether highly unlikely but disastrous outcomes should drive rational climate change policy (Weitzman 2008). A thorough inclusion of uncertainty in a quantitative assessment would require significantly more time and resources than available for the Copenhagen Consensus project. While these limitations reduce the direct applicability of the quantitative results derived in this study for policy, the qualitative results would most likely hold in an analysis which included uncertainty: an optimal climate change policy consists of a portfolio of mitigation measures; the allocation of costs over time should not follow an arbitrary rule but rather an optimal time path; and methane mitigation by itself cannot make a significant impact on climate change overall, but adds significant net benefits when combined with a CO_2 mitigation strategy.

APPENDIX: FUND MODEL

FUND (the Climate Framework for Uncertainty, Negotiation and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to a simple carbon cycle and climate model, and to a model predicting and monetizing welfare impacts. Climate change welfare impacts are monetarized in 1995 dollars and are modelled over 16 regions. Modelled welfare impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems (Link and Tol 2004). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. 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. Version 3.5, used in this paper, runs from 1950 to 3000 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the welfare impacts of climate change are assumed to depend in part on the impacts during the previous year, 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 impacts and monetized welfare impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to provide a proper long-term perspective. The remaining centuries are included to avoid endpoint problems for low discount rates, they have only a very minor impact on overall results.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk 1994). The period 1990-2000 is based on observations (http://earthtrends.wri.org). The 2000-2010 period is interpolated from the immediate past. The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett, Pepper et al. 1992). The period 2100-3000 is extrapolated.

The scenarios are defined by varied rates of population growth, economic growth, autonomous energy efficiency improvements, and decarbonization of energy use (autonomous carbon efficiency improvements), as well as by emissions of carbon dioxide from land use change, methane emissions, and nitrous oxide emissions.

Emission reduction of carbon dioxide, methane and nitrous oxide is specified as in Tol (2006). Simple cost curves are used for the economic impact of abatement, with limited scope for endogenous technological progress and interregional spillovers (Tol 2005).

The scenarios of economic growth are perturbed by the effects of climatic change. Climate-induced migration between the regions of the world causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible welfare impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the effect of carbon dioxide emission reductions on the economy and on emissions, and the effect of the damages on the economy 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 of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine *et al*. (1990). 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 temperature is derived by multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn, Schlesinger 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 of Kattenberg *et al.* (1996).

The climate welfare impact module, based on Tol (2002; 2002) includes the following categories: agriculture, forestry, hurricanes, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages are triggered by either the rate of temperature change (benchmarked at 0.04°C/yr) or the level of temperature change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol 2002).

In the model individuals can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all welfare impacts of climate change, 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 (cf. Cline 1992). The value of emigration is set to be three times the per capita income (Tol 1995; Tol 1996), 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 modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser 1994). 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 (cf. Fankhauser 1994). The wetland value is assumed to have a 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 welfare impact categories, such as agriculture, forestry, hurricanes, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol 2002). Modelled effects 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 (cf. Tol 2002).

The welfare impacts of climate change on coastal zones, forestry, hurricanes, 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 (cf. Tol 2002).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth) and heat-related disorders (with urbanization), or more valuable, such as ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol 2002).

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The science is clear. Human-caused global warming is a problem that we must confront.

But which response to global warming will be best for the planet? The Copenhagen Consensus Center believes that it is vital to hold a global discussion on this topic.

The world turned to scientists to tell us about the problem of global warming. Now, we need to ensure that we have a solid scientific foundation when we choose global warming's solution. That is why the Copenhagen Consensus Center has commissioned research papers from specialist climate economists, outlining the costs and benefits of each way to respond to global warming.

It is the Copenhagen Consensus Center's view that the best solution to global warming will be the one that achieves the most 'good' for the lowest cost. To identify this solution and to further advance debate, the Copenhagen Consensus Center has assembled an Expert Panel of five world-class economists – including three recipients of the Nobel Prize –to deliberate on which solution to climate change would be most effective.

It is the Copenhagen Consensus Center's hope that this research will help provide a foundation for an informed debate about the best way to respond to this threat.

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