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ABSTRACT

Given the large uncertainties in the climate science and in assessments of climate change impacts, the estimated expected economic benefits of emissions reductions are very uncertain. A relevant alternative to benefit estimates is to base policies on acceptable levels of climate change such as the widely supported 2 K target.

Methane is the second most important anthropogenic greenhouse gas only preceded by carbon dioxide. Methane has a relatively short atmospheric short-life time and therefore it has other economic characteristics than carbon dioxide. For example, if the ultimate aim of international climate policy is to stabilise the global average surface temperature to 2 K above the pre-industrial level at lowest possible cost, the current relative value of reducing methane as compared to carbon dioxide should be lower than its Global Warming Potential (GWP) value used in the Kyoto Protocol. However, this result is changed to the opposite if one adopts a cost-benefit approach.

Methane is also an important precursor to tropospheric ozone. Tropospheric ozone has in turn serious consequences on human health, agricultural production and ecosystems. Taking into account this in social cost/shadow price estimates of methane can increase the value considerably, in the order of 100 %. Consequently, the benefit cost ratios of methane mitigation are strongly dependent on which approach is adopted when valuing methane's economic impacts and if the tropospheric ozone co-benefit of methane mitigation is considered or not.

Many sources of methane are non-point emission sources. This makes it harder to regulate and control methane emissions than most carbon dioxide emissions. The most important single sector emitting methane is livestock production. The technical measures available to reduce emissions from livestock are small. The combination of being a non-point emission source and having few technical abatement measures implies that output based policies may be appropriate policies for reducing these emissions. Our back of the envelope estimates point to a benefit-cost ratio of about 2 of having a beef meet tax on US$ 1 in OECD countries. This would reduce global emissions by 30 to 70 M ton CO2 equivalents per year using GWP calculated over 100 years.

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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

1 INTRODUCTION

The "Assessment Paper on Methane Mitigation" by Kemfert and Schill presents an up to date and very comprehensive overview of estimates of methane abatement costs. What we want to focus on in this perspective paper is related to four issues which we believe are important and that has not been dealt with in any considerably length in Kemfert & Schill. The points are:

- the effect of methane and carbon dioxide emissions on the global average surface temperature,
- shadow prices and marginal social costs of methane and carbon dioxide,
- methane's impact on the global tropospheric ozone level and the economic benefits related to tropospheric ozone of methane abatement, and
- to present one additional abatement solution, namely output taxes on beef meat as an option to reduce methane (and other greenhouse gases).

For all calculations in the paper we focus on year 2020.This is within the time horizon considered in this Copenhagen Consensus Project.

However, we start to present our perspective on climate change and on the issue of cost-benefit versus cost-effectiveness analysis when evaluating abatement options.

2 THE CLIMATE CHALLENGE

Climate change is a reality with a warming of the earth as result. Current trends in the most relevant climate indicators are inline with what can be expected from climate models, e.g., the global heat content of oceans has increased significantly the last decades, the global average sea level is rising, the global average surface temperature has an increasing long-term trend. If nothing is done to reduce the emissions of greenhouse gases the global average surface temperature is estimated by the Intergovernmental Panel on Climate Change (IPCC) to increase between about 2 and 7 degrees Celsius above the pre-industrial level by year 2100 and with continuing warming thereafter (IPCC, 2007; Solomon et al, 2009). Temperature scenarios at the higher range of the interval would both imply a global average temperature level and a rate of change in the temperature not witnessed for millions of years (Jansen et al, 2007).

Even for less severe, and more likely temperature scenarios, serious negative impacts on ecosystems and society are expected to occur, see for example Warren (2006), Parry (2007) and Smith et al (2009). Even though there may be some positive economic impacts for small changes in the climate, these will mainly occur in developed countries, while developing countries, which in general are more dependent on agricultural activities, already have a warmer climate and have less resource for adapting to changes in it, are expected to suffer already from small changes in the climate. The overall picture concerning the negative impacts of climate change is more serious today than it was about a decade ago, see Smith et al (2009) where this is illustrated in an updated version of the "reasons for concern" diagram.

3 BENEFIT CALCULATIONS AND TARGETS

Due to the complexity of climate change and the deep structural uncertainty in the science the expected benefits of emission reductions can be found to be very large and strongly depending on arbitrarily set upper bounds on the climate sensitivity or on the damages caused by an increase in the global average surface temperature (Dasgupta, 2008; Weitzman, 2009). Similar arguments concerning the application of cost-benefit analysis for climate change have been around in the literature for more than a decade, e.g., Azar (1998), although it has not been shown as rigorously before as Weitzman recently did. Given this, it is not controversial, even for economists working in the field, see for example Dasgupta (2008) and Tol (2009), if one argues for more stringent climate policies than what can be justified by a formal cost-benefit calculation. How large such a risk premium that warrants a more stringent climate policy should be is, however, not easily quantified.

Moreover, besides the problems with structural uncertainties, existing benefit functions are likely to underestimate the benefits of emissions reductions. Very few of these benefit estimates includes the cost of large-scale surprises, non-market costs and no existing benefit function tries to capture socially contingent damages (Warren et al, 2006; Watkiss & Downing, 2008). In the few cases where the costs of large scale surprises are considered, the probabilities of these are likely to be underestimated, see Kriegler et al (2009).

An alternative approach to cost-benefit analysis for approaching the challenge of climate change is to base the reasoning on the close to globally adopted United Nations Framework Convention on Climate Change (UNFCCC). The overarching aim of the UNFCCC is "s***tabilisation of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system***". Even though this rather vague political aim is hard to transform into more clear-cut formulations on targets, there is a growing support for a long-term stabilisation of the global average surface temperature at or about 2 K above the pre-industrial level. This target is supported by a large group of scientists, see for example Richardson et al, (2009) and Allan et al, (2007), and has recently been given support by the G8 and MEF countries[1]. Currently, countries that contain a majority of the world's population have now expressed support for a 2 K target.

Given the widespread support of the 2 K target and the well known problems with benefit functions as discussed above, we will in section 5 complement the benefit calculations in Kemfert & Schill with a cost-effectiveness approach. By this we mean that we calculate shadow prices on methane and carbon dioxide in an optimizing integrated assessment model where the 2 K target is implemented as a constraint and use these shadow prices as "benefits" for calculating benefit-cost ratios. We believe that this is a more policy relevant approach than the use of social cost estimates based on benefit functions.

1 Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, the United States, China, India, Brazil, Korea, Mexico, South Africa, Australia and the remaining countries in European Union

4 METHANE VS. CARBON DIOXIDE

As discussed by Kemfert and Schill it is important to abate methane and other greenhouse gases and not only carbon dioxide. Clearly it would be a waste of money if not as many sources of emissions of greenhouse gases as possible where targeted for abatement strategies. This multigas approach to climate change is not new, cost-effectiveness was the main reason why a basket approach was adopted in the Kyoto Protocol.

When allocating resources to mitigate the adverse effects of climate change it is central to understand the dynamics (both the economic dynamics and climate dynamics) of different mitigation options. Even though Kemfert and Schill discuss this briefly we believe it deserves more attention and devote two sections to discuss temperature dynamics and social costs/ shadow prices. In this section we focus on the temperature dynamics of an emissions pulse of a short-lived greenhouse gas being methane and of the most important and long-lived greenhouse gas being carbon dioxide and in the next section we turn to the economic side of it.

As discussed by Kemfert and Schill, the atmospheric perturbation life-time of methane is about 12 years, while the perturbation life time for carbon dioxide can not be accurately described by a single time constant. Rather, a multitude of different time constants are needed in order to reflect the different time scales of which carbon dioxide equilibrates between atmosphere, oceans, biomass, soil, sediments and rocks (Archer et al, 2009).

So as to compare and illustrate the effect on the temperature of emitting of CO_2 and CH_4 we calculate the temperature response of a 100 M ton CO_2 emissions pulse and of a 1 M ton CH_4 emissions pulse by using an upwelling-diffusion energy balance model where the climate sensitivity is set to 3 K. The reason for assuming unequally large pulses is that methane is a considerably stronger greenhouse gas than carbon dioxide and that we want to fit the two curves in the same diagram. Note that the indirect effects on radiative forcing induced by methane emissions are taken into account. As Kemfert and Schill writes, methane contributes to an increased level of tropospheric ozone and to stratospheric water vapour and these enhances the direct forcing strength of methane by about 30 to 40 % (Forster et al, 2007)[2].

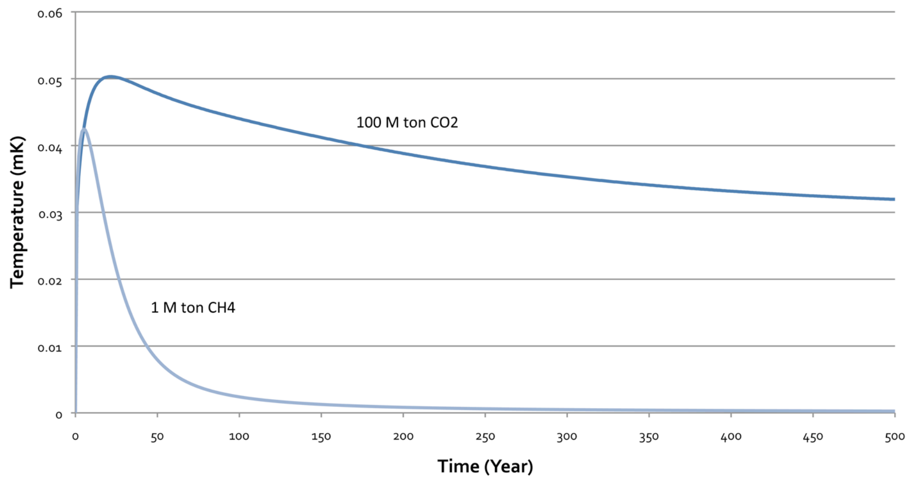
The result of this calculation is summarised in figure 1 and in the following bullets.

- Methane is a considerably stronger greenhouse gas then carbon dioxide. For short time horizons (less than 10 years) the effect on the temperature is about 100 times as strong for equally sized emission pulses.
- An emission pulse of methane has an effect on the global average surface temperature far longer in time than the atmospheric perturbation life-time of methane. This is due to inertia in the climate system.
- Even though the temperature response of a methane pulse lingers on for more than a century, the effect on the temperature decays considerably faster than for an emission pulse of carbon dioxide. Emissions of CO_2 has in principle an irreversible effect on the global average surface temperature, while methane has not, see also Solomon et al (2009) and Matthews & Caldeira (2008).

2 The total radiative forcing contribution from methane emissions are 0.6 to 0.7 W/m2, i.e., close to half of that of CO_2, if the indirect effects are taken into account.

- For equally sized emissions pulses of methane and carbon dioxide the effect of the CO_2 pulse on global average surface temperature would surpass that of CH_4 after about 400 years.

Figure 1. The temperature response following emissions pulses of CO2 and CH4.



Note that the CO2 emissions pulse is 100 times larger than the CH4 emissions pulse.

5 SOCIAL COSTS AND SHADOW PRICES

Kemfert & Schill use social cost of carbon estimates from Tol (2008) together with the CO_2 equivalent abatement potential for methane as reported in the abatement cost studies (primarily USEPA(2006)) when calculating the benefit-cost ratios. Although Kemfert and Schill are not explicit on that they use Global Warming Potential calculated over a time horizon of 100 years, they implicitly do so since that is the approach taken in the abatement cost studies. In USEPA (2006) the conversion factor for one ton of methane to ton carbon dioxide equivalents is 21, i.e., the climate impact of 1 ton of methane is said to be equal to 21 tons of carbon dioxide. As written by Kemfert and Schill this combination of social cost of carbon and GWP is inconsistent.

In this section we will calculate the social cost of methane (and carbon dioxide) using a cost-benefit approach and the shadow price of methane (and carbon dioxide) assuming a globally adopted 2 K target and analyse how these numbers depend on the discount rate and the climate sensitivity[3]. This is done to get consistent estimates on the social cost and shadow price of methane (and carbon dioxide), to illustrate the very large uncertainty in such estimates and to show the strong dependence on the discount rate.

We will not perform any new calculations concerning GWP and its physically based alternative metrics, we refer to Forster (2007) and Fuglestvedt et al (2003) for such discussions.

3 In a technical sense both the social cost and the shadow price are shadow prices, we, however, refer to social cost when discussing results from the cost-benefit cases and shadow price when discussing results from the cost-effectiveness cases.

We use an updated version of the globally aggregated climate-economy model MiMiC when estimating the social costs and shadow prices. The model is presented in detail in Johansson et al (2006, 2008), see also appendix A for a brief presentation. We estimate the social costs and shadow prices given three different climate sensitivities[4], 2 K (a low value), 3 K (best estimate), 4.5 K (a high value). For simplicity (and lack of time) we do not separate out discounting due to economic growth, elasticity of marginal utility of consumption and pure rate of time preference, instead we presuppose three different discount rates; 1 %, 3 % and 5 % per year. The low rate is inline with the rates used by for example Stern (2007) and the high rate is inline with the rates used by for example Nordhaus (2008). In the recommendations from the Copenhagen Consensus Centre a discount rate of 3 % is suggested. We adopt this as the main case in this paper.

When estimating social cost of methane and carbon dioxide we adopt the quadratic damage function used in Nordhaus (2008). Our baseline scenarios for gross world production and emissions of greenhouse gases are from IIASA A2r (IIASA, 2009). Economic growth is exogenous in MiMiC. As discussed above in section 3, existing damage functions (including the one used here) are likely to underestimate actual damage for a given temperature level. The objective of the MiMiC model is to minimize the net present value of the sum of the climate damages and the abatement costs for the three most important well mixed greenhouse gases, carbon dioxide, methane and nitrous oxide. Consequently, the emissions of these greenhouse gases are endogenously determined in the model.

When estimating the shadow price for methane and carbon dioxide we run the MiMiC model with the 2 K target as a constraint and minimize the net present value of the cost of abatement. In this case the damages of the temperature increase are not considered.

Both the cost-benefit approach and the cost-effectiveness approach suffer from the large uncertainties concerning the cost of abatement. Technical improvements leading to declining abatement costs are exogenous in the model.

5.1 Social costs

The social cost of methane and the ratio of the social cost of methane to social cost of carbon dioxide depends strongly on the climate sensitivity and the discount rate, see table 1. The ratio is clearly declining with declining discount rate. This comes as no surprise since emissions of CO_2 have a significantly longer lasting effect on the temperature than emissions of methane. Hence, given the shorter life-time of methane (and the shorter corresponding effect on the temperature) the social cost of methane is less sensitivity to the discount rate as compared to the social cost of carbon dioxide. The ratio of the social costs of methane to carbon dioxide can be interpreted as an alternative conversion factor to the GWP, see Reilly & Richards (1993) & Kandlikar (1995). Hence, if the GWP value is 21 (as used in the Kyoto Protocol or 25 as in the latest IPCC assessment), the GWP approach undervalues the relative importance of reducing methane as compared to carbon dioxide unless the discount rate is

4 The climate sensitivity is explained by the IPCC (2007) as follows "The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the global average surface warming following a doubling of carbon dioxide concentrations. It is likely to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C."

low. As can be expected the social cost of methane and carbon dioxide increases strongly with climate sensitivity.

The two extremes for the social cost of methane in our calculation are 210 US$/ton CH_4 on the lower end and 1700 US$/ton CH_4 on the higher end (while the corresponding numbers for CO_2 are 3.7 US$/ton CO_2 and 78 US$/ton CO_2). These numbers can be compared to the numbers (implicitly) assumed by Kemfert and Schill which are 275 US$/t CH_4, 407 US$/t CH_4 and 974 US$/t CH_4[5] (while their numbers for CO_2, taken from Tol (2008), are 13.1 US$/t CO_2, 19.4 US$/t CO_2 and 46.4 US$/t CO_2). Hence, even though Kemfert & Schill use an inconsistent approach, their assumptions on the benefit side seem to be roughly in line with our results on the social costs of methane, but without including the upper level of our estimate.

Table 1. Cost-benefit case. The social cost of methane in year 2020 (US$/per ton CH4).

Discount rate	Climate Sensitivity (K)		
	2 K	3 K	4.5 K
	(US$ / t CH_4)	*(US$ / t CH_4)*	*(US$ / t CH_4)*
1 %	600 (21)	1000 (22)	1700 (22)
3 %	320 (42)	520 (42)	780 (42)
5 %	210 (58)	320 (58)	470 (58)

The ratio of the social cost of methane to that of carbon dioxide is shown within the brackets. The social cost of carbon dioxide is obtained by dividing the social cost of methane with the ratio given within the brackets.

5.2 Shadow prices

Given the widespread political support for a global temperature target of 2 K above the pre-industrial level, we believe that it is more policy relevant to focus on shadow prices obtained from models where such a target is taken account. Taken such an approach alters the relative importance of reducing methane as compared to carbon dioxide. Hence, the ratio of the shadow price of methane to carbon dioxide in year 2020 is considerably lower than for the ratio of social costs discussed in the previous sub-section, compare table 1 and 2, see also Manne & Richels (2001). The reason is that the temperature response prior to the date that the constraint (i.e., the 2 K targets) starts to bite does not influence the shadow price of an emission pulse. Given the relatively short life-time of the temperature response of methane reductions and that the target will be met beyond the middle of this century the shadow price of methane will be relatively low compared to what is found in the cost-benefit analysis or to its GWP value calculated over 100 years. The case is different for carbon dioxide since it has an almost irreversible effect on the temperature. Hence, given a cost-effectiveness approach (with a 2 K target) the use GWP overvalues the importance of reducing methane in year 2020, and correspondingly, relatively more economic resources should be devoted to reduce long-lived greenhouse gases such as carbon dioxide, see also van Vuuren et al (2006).

5 The values for the social cost of carbon dioxide that Kemfert & Schill uses are converted to estimates of the social cost of methane by using a GWP equal to 21. As written above this conversion is somewhat inappropriate, but the methodology (implicitly) used by Kemfert and Schill.

Table 2. Cost-effectiveness case. The shadow price of methane in year 2020.

Discount rate	Climate Sensitivity (K)		
	2 K	3 K	4.5 K
	(US$ / t CH_4)	*(US$ / t CH_4)*	*(US$ / t CH_4)*
1 %	260 (3.3)	550 (3.7)	3700 (5.0)
3 %	120 (5.5)	330 (5.7)	980 (6.3)
5 %	65 (7.9)	250 (9.2)	740 (9.8)

The ratio of the shadow price of methane to that of carbon dioxide is shown within the brackets. The shadow price of carbon dioxide is obtained by dividing the shadow price of methane with the ratio given within the brackets.

A cost-effectiveness approach does in general imply lower shadows prices on methane as compared to the social costs obtained from the cost-benefit approach. It is only in the case where a high climate sensitivity is assumed where the shadow price is higher in the cost-effectiveness case than in the cost-benefit case. The situation is different for carbon dioxide where the shadow prices are higher than the social costs for all separate cases.

As written above, our recommendation concerning main case is to use a discount rate of 3 %, a climate sensitivity of 3 K and a cost-effectiveness approach with a 2 K target for the global average surface temperature. This implies a shadow price of methane emissions equal to 330 US$/t CH_4 and a shadow price of CO_2 emissions equal to 57 US$/t CO_2 in year 2020[6].

Finally, if economic efficiency is a primary aim GWP should not be used to assess and compare benefits of methane abatement with other abatement options, such as CO_2 abatement. GWP calculated over 100 years will overvalue the importance of reducing short-lived greenhouse gases as compared to long-lived gases if the aim is to stabilise the global average surface temperature at 2 K. Given the use of a cost-benefit approach GWP will in general undervalue the importance of reducing methane as compared to long-lived greenhouse gases such as carbon dioxide[7]. Setting aside efficiency, there is political support for the GWP value calculated over a 100 year time period. This approach is adopted within the Kyoto protocol and it would most likely be politically difficult to change metric. Also, estimates on the costs of using the GWP approach instead of an optimal approach of valuing different greenhouse gas emissions are estimated to be rather small, less than about 5-10 % (Johansson, 2006).

6 METHANE AND TROPOSPHERIC OZONE

Methane is an important precursor to the increased background level of tropospheric ozone. Tropospheric ozone[8] carries along a lot of other impacts besides being a greenhouse gas. It has serious negative impacts on human health, ecosystems and forest and agricultural

6 These values will increase over time beyond year 2020.

7 Note that we have assumed full global cooperation in both the cost-benefit case and the cost-effectiveness case. The general result concerning the relative valuation of methane to carbon dioxide per ton emission should not change considerably if partial cooperation was assumed in the modelling.

8 Note that tropospheric ozone is not a primary pollutant but created through reactions by precursors, such as methane, nitrogen oxides, carbon monoxide and volatile organic compounds.

productivity[9]. It is only recently that abetment of methane has been considered as an option to reduce tropospheric ozone levels. Historically, tropospheric ozone has been approached as a local and/or regional atmospheric environmental problem and the policies in place to reduce the tropospheric ozone load have focused on precursor important on such a spatial scale (West & Fiore, 2005; The Royal Society, 2008). Methane on the other hand is globally well-mixed due to its relatively long atmospheric life-time and therefore affects the level of tropospheric ozone all over the globe.

We will touch upon two aspects concerning tropospheric ozone:

- Tropospheric ozone has a negative impact on the biospheric carbon stock.
- Tropospheric ozone carries along a range of health and economic problems. The economic impacts of these have been quantified in the academic literature and we briefly summarize what they imply for the social cost of methane.

6.1 Tropospheric ozone and the biospheric carbon stock

Tropospheric ozone is well known to have important impacts on plant physiology (Stitch, 2007; The Royal Society, 2008). Recent estimates have pointed to the fact that tropospheric ozone has a strong negative impact on the carbon stock in biomass and soil. Stitch et al (2007) suggests that by year 2100 the radiative forcing caused by elevated atmospheric CO_2 levels which are caused by a decrease in the CO_2 sink induced by tropospheric ozone may be higher than the direct global average radiative forcing of tropospheric ozone. The direct radiative forcing of troposperic ozone is estimated to be about 0.5-0.7 W/m^2 by year 2100. Today, methane is accountable for a roughly a fourth of the elevated average tropospheric ozone level and will remain important for the future concentration of tropospheric ozone. However, it is hard to judge given existing integrated assessment models how large this effect is on the social cost and shadow price of methane, but it would raise the numbers.

6.2 Non-climate co-benefits of methane mitigation

The non-climate related economic benefits of reducing tropospheric ozone through methane abatement have been assessed in West and Fiore (2005) and West et al (2006)[10]. The health impacts of tropospheric ozone are primarily associated with acute and chronic effects on the respiratory system and daily premature mortality, while the impact of tropospheric ozone on agricultural and forestry production is that it reduces the yields (West & Fiore, 2005; West et al, 2006; The Royal Society, 2008).

We base our calculations of the benefits of reducing the ozone level on West & Fiore (2005), West et al (2006) and West et al (2007). However, we update their calculations so that numbers consistent, concerning the discount rate, with the social costs/shadow prices presented in section 5 can be presented.

According to West and Fiore (2005) the non-mortality benefits of reducing tropospheric ozone is close to linear in concentration and can be divided into the following categories

9 Stratospheric ozone is important for capturing UV radiation, tropospheric ozone is not.
10 The literature on this topic is very sparse.

- Agricultural benefits = US$ 2.8 billion /yr/ppb O_3.
- Forestry benefits = US$ 1.7 billion /yr/ppb O_3.
- Human health (non-mortality) = US$ 3 billion /yr/ppb O_3.

West et al (2006) and West et al (2007) estimate the global mortality effects of changes in the global ozone concentration in year 2030. West et al (2007) present two scenarios from where we estimate a linear mortality tropospheric ozone relationship to about 32 000 mortalities per ppb of the population-weighted 8-h daily maximum ozone level. West et al (2006) presents a slightly lower value of 26 000 mortalities per ppb of the population-weighted annual average 8-h daily maximum ozone level. In both cases the global population is assumed to 9.17 billion. In the calculations presented below we will use the change in annual mean tropospheric ozone concentration instead of population weighed annual average 8-h daily maximums and assume 30 000 mortalities per ppb of the global average tropospheric ozone. The use of an annual mean instead of population weighed annual average 8-h daily maximums implies that we will underestimate the impacts on mortalities of reducing the ozone level[11]. Further, we estimate from Shindell et al (2005), West & Fiore (2005) and Fiore et al (2008) that one ppb change in atmospheric CH_4 gives on average over the globe a change of 0.004 ppb O_3. As written in the beginning of this section, the effect of changing the atmospheric concentration of methane has a global impact on the ozone concentration. However, the local impact on the ozone level depends on chemical and metrological conditions and is not uniform over the globe. Also, 1 M ton of atmospheric CH_4 corresponds to 0.3646 ppb CH_4 (Tanaka, 2008).

In order to estimates the social cost of methane through its effect on the non-climate impact of tropospheric ozone we have to assign a Value of a Statistical Life (VSL). We take the assumption in West et al (2006) and set global average VSL to US$1 million. As an alternative we include a rather high global average VSL of US$ 3 million. We scale the mortalities per ppb tropospheric ozone to the global population. The population is assumed to be 7.8 billion by 2020 and there after to grow with 1 % per year[12].

As seen in table 3, the non-climate benefits of abating methane through its effect on tropospheric ozone is comparable in size to the social cost estimates in table 1 and the shadow prices in table 2. The non-climate benefits of methane reduction are strongly dependent on the VSL assumption, but not very strongly dependent on the discount rate, due to the relative short life time of methane[13]. To get the numbers in table 3 directly comparable to benefit numbers in Kemfert and Schill they should be divided by methane's (old) GWP value of 21.

If these non-climate benefits of methane abatement were taken into account in the benefit-cost ratios presented in Kemfert & Schill these ratios would roughly double. However, even if we believe that it is important to recognise these benefits when suggesting climate related measures we hold the position than they should be of second order importance since they are not climate benefits. Besides, the literature on this topic is sparse and the numbers uncertain.

11 From West et al (2006) we estimate that we will underestimate the mortalities by about 40 %.
12 The population projection is set to roughly equal the scenario in the IIASA A2r scenario.
13 Note that there is a difference in the time dynamics of the impacts on ozone and temperature following changes in methane emissions. In the latter case the effect is dependent on the inertia of the climate system while in the former case it is not. Hence, the effect on the ozone level decays with methane's perturbation life time of 12 years.

Finally, the calculation presented in this section was done given immensely large simplifications of the atmospheric chemistry, still the calculation produce meaningful results since they are based on results from advanced models (West et al, 2006, 2007; Fiore & West (2005)) and by that methane has a global impact on the tropospheric ozone level. There are also a range of additional uncertainties that we have not assessed here. Thus, the uncertainty is larger than what is presented in table 3. Our benefit estimates are higher than what is found in West et al (2006). The reason for this is a result of that they only considered the benefits from methane abatement over a rather limited period of time.

Table 3. Social cost of methane through its effect on non-climate impacts of tropospheric ozone.

Discount rate	VSL = 1 million	VSL = 3 million
	(US$ / t CH_4)	*(US$ / t CH_4)*
1 %	580	1500
3 %	470	1200
5 %	390	930

7 CLIMATE TAX ON BEEF MEAT

As discussed in Kemfert & Schill some abatement option may have considerable implementation barriers. For example, there are cheap options to reduce methane from ruminants, and measures to reduce emissions from rice fields, but how should a policy be constructed so that these abatement options are realised efficiently? Actors are in general small in scale, geographically scattered and the emissions hard to monitor. Also, for livestock management the low cost abatement potential is small, e.g., the abatement potential below a marginal cost of 60 US$/t CO_2 equivalents are less than 10 % of the methane emissions from that sub-sector.

Beef production does not only cause large methane emissions, but also indirectly large emissions of nitrous oxide (N_2O) per produced kg of meat, and some CO_2, leaving aside induced deforestation. In total the greenhouse gas emission per eatable unit of energy of beef is around 8 times higher than for poultry, and 50 times higher than for beans when emissions are converted to CO_2 equivalents using GWPs calculated over 100 years. Due to these large differences in emissions between different food stuff, a changed diet, containing less beef, could decrease the greenhouse gas emission considerable (Carlsson-Kanyama & González, 2009; Stehfest et al, 2009; Wirsenius et al, 2009). Using a nutritious and healthy diet as the norm, it is obvious that there is a considerable substitutability between different sorts of food from a nutritional perspective. Substitutability is still substantial when considering the prevailing preferences for meaty texture, since several different meat types are available, as well as vegetable-based meat substitutes.

These aspects point towards that output based policies may be a realistic alternative, at least in the developed countries where food security is less of a problem. See for example Hoel (1998), Schmutzler & Goulder (1997) and Sterner (2003) for discussions on when output taxes may be the suitable policy of choice to curb emissions. Changing the diet of the people is a difficult and controversial issue. However, output taxes on gasoline have changed peoples driving patterns as well as the energy efficiency of vehicles. Similar effect could be achieved by introducing a greenhouse weighted consumption tax on beef. In this section we will analyze the benefit-cost ratio of a tax on beef in OECD countries as policy to reduce beef consumption and thereby methane and other greenhouse gas emissions.

To give a tentative back of the envelope estimate of the cost of the tax we calculate the deadweight loss of the tax under two cases and interpret those as the cost of the policy[14]. The two cases are:

1. The ruminant market in OECD is assumed being a closed economy and we only account for own price effects.
2. The ruminant market in OECD is assumed being small open economy. Also in this case we only account for own price effects.

Given the size of the OECD, the former case is probably a better approximation than the latter.

A demand price elasticity of -1.3 is assumed based on Allais and Nichele (2007) and Burton and Young (1991) and a supply price elasticity of 1 based on Banse et al (2005). Both the demand and supply elasticities are based on data for the EU. The supply elasticity is only of importance in the closed economy case since the producer price is unaffected in the small open economy case. The OECD average retail price of beef meat products is estimated to US$ 12 per kg and a simple linear extrapolation is used to project the baseline beef consumption in the OECD countries to 28160 kton carcass weight in 2020 (FAOSTAT, 2009).

The life cycle greenhouse gas emissions from reduced beef consumption are estimated to be about 25 kg CO_2-eq / kg beef in carcass weight (Williams et al, 2006). Combining with data from Cederberg et al (2009), we estimate the emission of CH_4 to 0.7 kg /kg beef and the N_2O emissions to 0.02 kg/kg beef and 3 kg of CO_2/kg beef. Since several greenhouse gases are involved, their relative weight is of crucial importantance for the B/C ratios. For that reason we study three cases, one case that corresponds to Kemfert & Schill's case with a carbon dioxide price of 46 US$/t CO_2 and using GWP calculated over 100 years as the relative weights for the different gases, a case where shadow prices of emissions are based on a cost-effective approach with a climate sensitivity of 3 K and a discount rate of 3%[15], see table 2, and a case where also the non-climate co-benefits of tropospheric ozone assuming a VSP of 1 million US$ is included, see table 3.

Our results show that the abatement level is about twice as large in the small open economy case as in the closed economy case for a given tax level. However, the B/C ratios vary very little between the two cases, less than 0.1. For that reason only the B/C ratio for the closed

14 This should been seen a very rough and first estimate, to getter better results an agriculture sector model where existing subsidies and policies are taken into account should be used. Given the time frame for this project there was no time to do such a calculation.

15 In this case the relative value of nitrous oxide to carbon dioxide is 300.

economy case is presented in table 4. We can also see that a low tax on beef has a fairly high B/C ratio.

Reduced beef consumption has additional benefits to those discussed above. Most importantly, land required for the global agricultural system would be reduced if beef consumption is reduced. Cattle ranching is a major driver of tropical deforestation, and reduced consumption of beef in the OECD countries would alleviate some of the pressure on the tropical forests as land prices would probably drop. This aspect suggests that the B/C ratio would be higher for a beef tax than what we have estimated here. Furthermore, decreased land demand and reduced land prices will increase the cost-effective potential of using bioenergy as a carbon mitigation option in the energy system (Wiresnius et al 2009).

Table 4. Reductions in beef meat consumption due to a beef tax in OECD, and the greenhouse gas mitigation expressed in GWP calculated over 100 years.

Tax on ruminant meat	Open small economy		Closed economy		B/C ratios		
(US$ / kg beef)	Reduction (kt meat)	Reduction (M ton CO_2-eq)	Reduction (kt meat)	Reduction (M ton CO_2-eq)	Base case	Cost-effective	Cost-eff and ozone
0.5	1455	36	657	16	4.7	3.3	4.7
1	2783	70	1302	33	2.4	1.7	2.4
2	5114	128	2555	64	1.2	0.9	1.2
3	7091	177	3759	94	0.8	0.6	0.8

The B/C ratios are presented for Kemfert & Schill's high benefit case, assuming a carbon price of 46 US$/CO2-eq, and cost-effective case with a climate sensitivity of 3 K and a discount rate of 3 %, and finally a cost-effective case with the ozone co-benefit included, assuming a VSL of 1 million US$.

8 RECOMMENDATIONS AND CONCLUSIONS

As written in the introduction we find ourselves in agreement with the abatement estimates presented in Kemfert & Schill. Instead of discussing these abatement measures in detail we have mainly discussed aspects related to the benefit estimates of methane. As we wrote in section 3 there are serious problems with benefit estimates concerning climate measures. For that reason we recommend the use of shadow prices estimated from models with specific climate targets. We therefore suggest that the Copenhagen Consensus should use shadow prices estimated from integrated assessment models where the widely supported 2 K target is taken into account. We further suggest that the shadow prices are estimated assuming a climate sensitivity of 3 K and a discount rate of 3 %. By using these midrange estimates for our calculation, we end up with shadow prices that slightly supersede the high social cost of carbon presented by Kemfert & Schill of 46 US$/t CO_2 . To support shadow prices of around 15 US$/ton CO_2, also presented by Kemfert and Schill, we either have to assume a less stringent climate target or assuming a low climate sensitivity and a discount rate of 5 %.

Even though we support the assumption of a carbon price of about 50 US$/t CO_2, the cost-effective approach prescribe that the relative valuation of methane is considerable lower than estimated using the GWP calculated over 100 years. Instead of valuing methane as 21 high as CO_2 per ton emission as Kemfert and Schill implicitly do, we suggest that methane should only be valued about 6 time as high, see section 5 and table 2.

When considering that methane is an important precursor to the global level of tropospheric ozone, the relative value of methane emissions should, however, increase. By assuming that a global average value of a statistical life is US$ 1 million, the ozone related benefit of methane mitigation more than double the cost-effective valuation of methane, see section 6 and table 3. However, the literature concerning the non-climate tropospheric ozone benefits of methane abatement is sparse. The numbers should therefore be seen as rather preliminary.

Thus, taking a cost-effectiveness approach (assuming a 2 K target, a climate sensitivity of 3 K and a discount rate of 3 %) and valuing the non-climate benefit of tropospheric ozone, the B/C numbers presented in Kemfert and Schill with a SCC of 46 US$/t CO_2 should roughly be in line what we suggest. If the expert panel appointed by the Copenhagen Consensus Centre prefers another approach, the relative weight of methane should be adjusted accordingly, based on table 1, 2 and 3. Also, we find little support for using either of Kemfert & Schill's two lowest (implicit assumptions) on the social cost/shadow price of methane if methane's impact on tropospheric ozone is considered.

As discussed by Kemfert and Schill many sources of methane are non-point emission sources. This makes it harder to regulate and control methane emissions from these sources than, for example, the pricing of carbon dioxide emissions from fossil fuels. Still, Kemfert and Schill recommend using their portfolio 1, which includes several mitigation options in the agricultural sector, unless policy makers find the implementation barriers too large. They also argue that mitigation efforts of methane should be spread over several sectors to diversify risk. We claim that there are reasons to diversify risk for climate mitigation as a whole, but not for measures targeting only methane. Furthermore, we argue that there are three reasons why policy makers should not rely to any large extent on technical mitigation options in the agricultural sector as for now. First, as Kemfert and Schill also point out, the engineering cost estimates may be in reality higher for several reasons, e.g., transactions costs and intangible costs are not taken into account and may be large. Secondly, we are not convinced that there are not significant indirect emissions of GHG for some mitigation options. For instance, adding fat to the cattle feed to reduce the methane emissions from enteric fermentation could lead to large indirect emissions. Oil crops often cause quite large N_2O emissions, and maybe even more important, palm oil is a major driver of deforestation in Malaysia and Indonesia, thus causing large CO_2 emissions. Finally, there are yet no convincing policy instruments suggested in the literature that would induce methane abatement measures in the agricultural sector. As the emissions hardly can be taxed directly or included in permit trading schemes, due to high monitoring costs, it is hard to provide reliable incentives to farmers to adopt the measures.

For these reasons we suggest to focus primarily on methane emissions from solid waste management, coal mine methane and natural gas, thus aiming at the large scale sources which are easy to monitor. The possibility for successful implementation is much larger. If emissions in the agricultural sector are to be targeted we suggest a tax of around 1 US$/ kg beef (carcass weight) to affect the diets of people in the OECD countries. This policy is, if it gained political acceptance, fairly easy to implement.

Just as Kemfert and Schill point out that their estimates are very rough we would like to do that to concerning our estimates. We have tried to give crude numbers on how to adjust Kemfert and Schill's benefit-cost ratios to be consistent with a cost-effectiveness approach, and have added the benefit methane abatement has on tropospheric ozone. If the expert panel appointed by the Copenhagen Consensus Centre prefers a cost-benefit approach to climate change we have provided numbers so benefit-cost ratios can be calculated given such an approach. In addition, we have also provided rough and preliminary numbers on the benefit-cost ratio of a beef tax. All these calculations are inherently uncertain due to both parametric and structural uncertainties and simplifications. Especially the beef tax calculation should be seen as very tentative. Still, we think that our estimates complements the data provided by Kemfert and Schill and also give guidance for the Copenhagen Consensus on some crucial aspects in order to make a consistent assessment of different mitigation efforts.

APPENDIX A. THE MIMIC MODEL

The Multigas Mitigation Climate (MiMiC) model is a globally aggregated optimizing integrated assessment model. The version used here is an updated version of the MiMiC model presented and used in Johansson et al (2006, 2008). The main differences between the model used here and the versions in Johansson et al (2006, 2008) are that the energy balance module has been improved (by the use of an upwelling-diffusion energy balance model), the carbon sink has been recalibrated, climate-feedbacks on the carbon cycle are taken into account and updated data are used to initialize and fit the model to historical global average radiative forcing and surface temperature levels.

The model runs between the years 1880-2200 with yearly time steps over the period 1880 to 2004 and with 5 year time-steps over the period 2005 to 2200. The period 1880 to 2004 is used to calibrate the forcing strength of aerosols and initialize the carbon cycle model and the energy balance model.

CO_2 concentrations are modelled by a linear pulse representation of the Bern carbon cycle model based on Joos et al (1996). CH_4 and N_2O concentrations are modeled using the global mean mass-balance equations (Prather & Ehhalt, et al., 2001), taking the feedback effect CH_4 has on its own atmospheric lifetime into account. The equations for radiative forcing are the expressions given in TAR (Ramaswamy et al., 2001). We also include the indirect effect of methane concentration on tropospheric ozone and stratospheric water vapor concentrations (Wigley et al., 2002). The relationship between aerosols emissions and its direct and indirect radiative forcing is assumed to be linear.

The energy balance model used to calculate the temperature response from changes in the radiative forcing is based on a linear Upwelling Diffusion Energy Balance Model with polar overturning. The model is calibrated to emulate the global average surface response of AOGCMs, see Johansson (2009) more details.

Abatement costs are modelled with the aid of abatement cost functions. The abatement cost of CO_2 abatement are based on the EPPA model and the GET model, while the abatement cost of reducing methane and nitrous oxide is primarily based on EPA (2006) and EMF 21.

Baseline scenarios for the period 2010 to 2100 for CO_2, CH_4 and N_2O and for the Gross World Product are taken from the IIASA A2r scenario which is an updated version of the SRES A2 scenario; see Riahi et al (2006). After 2100 these scenarios are extrapolated. Abatement of emissions is only allowed from the year 2015 and onwards. CO_2 emissions from land use change follow the A2r scenario and no abatement of these emissions are considered.

The radiative forcing for halocarbons and aerosols are assumed to exogenously decline over time. For halocarbons the radiative forcing decline with 1 % per year. This decline rate correspond to the inverse of the atmospheric lifetime of the CFC with the highest forcing, i.e., CFC-12. For aerosols the radiative impact is constant at the year 2000 level up until to 2015 and then declines with 2 % per annum.

In the case when the model is run as a cost-benefit model the damage function from Nordhaus is used (2008). The climate sensitivity and discount rate is varied in this paper in order to show the great importance of these two parameters.

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