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The Impact of Climate Change on the Balanced-Growth-Equivalent: An Application of *FUND*

David Anthoff[1], Richard S.J. Tol[2]

Abstract: The *Stern Review* added balanced growth equivalences (BGE) to the economic climate change research agenda. We first propose rigorous definitions of the BGE for multiple regions and under uncertainty. We show that the change in the BGE is independent of the assumed scenario of per capita income. For comparable welfare economic assumptions as the *Stern Review*, we calculate lower changes in BGE between a business as usual scenario and one without climate impacts with the model FUND than the *Stern Review* found with the model PAGE. We find that optimal mitigation policies give even lower changes in BGE and argue that those policy choices should be the focus of the research effort rather than total damage estimates. Sensitivity analyses show that the *Stern Review* chose parameters that imply high impact estimates. However, for regionally disaggregated welfare functions, we find changes in BGE that are orders of magnitude higher than the results from the *Stern Review,* both for total damage as for optimal policy analysis. With regional disaggregation and high risk aversion, fat tails and with that very high welfare losses emerge.

Key words: Impacts of climate change, balanced growth equivalent, Stern Review

Corresponding author. Email: david@anthoff.de

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[1]. International Max Planck Research School on Earth System Modelling, Hamburg, Germany
Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany
[2] Economic and Social Research Institute, Dublin, Ireland
Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands
Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA

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1. Introduction

The *Stern Review of The Economics of Climate Change* (Stern *et al.*, 2006) has caused substantial discussion, not least about the validity of the headline conclusion that climate change would cause a welfare loss equivalent to a permanent income loss of 5 to 20%. The initial responses of many economists (Arrow, 2007; Dasgupta, 2007; Mendelsohn, 2006; Nordhaus, 2007a; Nordhaus, 2007b; Pielke Jr, 2007; Tol, 2006b; Tol and Yohe, 2007; Weitzman, 2007; Yohe *et al.*, 2007) focused on a variety of shortcomings of the research and the choice of the rates of pure time preference and risk aversion, but later reactions (Yohe and Tol, 2007; Weitzman, 2008) emphasized that the *Stern Review* has also brought renewed attention to the conceptual and moral difficulties of any economic appraisal of projects to limit climate change and its impacts.

This paper contributes in four ways to the ongoing debate about the conclusions of the *Stern Review*. First, this paper is a sensitivity analysis on the integrated assessment model used to derive the conclusions of the review. Second, we extend the analysis conducted by the *Stern Review* with a regionally disaggregated welfare module. Third, we not only calculate the difference between scenarios with and without climate impacts, but evaluate specific policies in terms of changes in balanced growth equivalents. Fourth, we propose a rigorous definition of the balanced growth equivalent, which was sadly lacking from the *Stern Review.*

The *Stern Review* diverged from the usual approaches of calculating the welfare impact of climate change employed in the literature (Pearce *et al.*, 1996; Smith *et al.*, 2001) in a number of ways. For one, it presented the results of its modeling exercise as changes in balanced growth equivalences (cf. Mirrlees and Stern, 1972). Previous studies of climate change had presented economic damages either as total impacts for a benchmark scenario (typically, the effect of a doubling of atmospheric carbon dioxide on today's population and economy), or as marginal impacts from the release of greenhouse gas emissions. The introduction of a new measure is certainly a refreshing move, but it makes comparison with previous results difficult. One could attempt to infer what the results from the *Stern Review* are in the measure units used in previous studies. In this paper we choose the other direction: We use the welfare measure used in the *Stern Review* but instead of using *PAGE*, the integrated assessment model employed for the *Stern Review*, we use the *FUND* model to calculate impacts of climate change scenarios. As such, this paper is analyses into how depended the results from the *Stern Review* are on the specific assumptions made in the *PAGE* model. We also run the model with more combinations of input parameters than the *Stern Review* did, in particular we investigate sensitivity to all IPCC SRES scenarios and more discounting schemes.

Mirrlees and Stern's (1972) definition of the balanced growth equivalent is for a single decision maker. It seems that the *Stern Review*'s calculation of welfare measures is based on globally averaged per capita income and total population figures[3]. The *Stern Review* suggests that a more appropriate aggregation would take up regional data when deriving the welfare measure. Due to time constraints, the *Stern Review* seems not to have carried out those calculations. Here, we do use regional impacts, income, and population data to estimate changes in the balanced growth equivalent due to climate change.

Finally, the *Stern Review* presented its results as differences between scenarios with no impacts from climate change at all and scenarios with climate change impacts. This cannot be regarded as an evaluation of policy options: There is no feasible policy option available today to avoid all climate change impacts in the future. A more meaningful result is obtained by looking at changes of welfare measures that would be achieved from actually possible policy options. We attempt to do this by presenting changes in welfare of optimal policy choices in comparison to business as usual scenarios that assume no climate change mitigation.

Section 2 reviews the original definition of balanced growth equivalence and shows our extension with non-constant populations, regional disaggregation, and uncertainty. Section 3 outlines the FUND model. Section 4 presents the numerical results. Section 5 concludes.

2. Balanced growth equivalent

2.1. Basic concept

Mirrlees and Stern (1972) introduced the concept of a *balanced growth equivalent* (BGE) as a commodity measure of welfare. The thought was that when looking at policy proposals one could calculate the change in BGE for a particular policy and use that as a rough first estimate whether further investigation of that policy would be warranted or whether the impact of that policy would be too small in the first place to warrant further research. The authors themselves suggest that there might be many broad economic policy options unexplored that

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[3] The actual review text is not clear on this point, but subsequent private communication with the *Stern Review* team confirmed this. Then again, different members of the Stern Review have issued contradictory statements, and occasionally changed their opinion on technical details.

would cause an increase of at least 1% in BGE and propose that those should attain more research time. Looking at policy impacts in terms of changes of a commodity welfare measure has the additional nice property that changes can be measured, even when the commodity measure is based on an ordinal welfare ordering. The BGE as a welfare measure has largely been ignored in the economics literature: only 9 papers refer to Mirrlees and Stern (1972) according to the Web of Science, and none of these papers develops the BGE further or applies it. Stern *et al.* (2006) appears to be the first application.

The following will briefly review the original concept with the notation used for this paper. Since we will later use a numerical model to run simulations, we use discrete time for the model, unlike the original specification of BGE. One key exercise of this paper is to compare the effects of various policy options with respect to climate change in terms of welfare changes. Policy choices are represented by ω. A specific policy choice ω could for example designate one specific carbon tax schedule. While in theory ω can stand for any policy out of all possible policy options, the numerical analysis later in the paper will restrict itself to a subset of policy options.

Let welfare for a specific policy ω be

$$(1) \qquad W(\omega)=\sum_{t=0}^{T}U\left(C_{\omega,t}\right)P_t\left(1+\rho\right)^{-t}$$

where $C_{\omega,t}$ is per capita consumption at time t as it results from choosing policy ω, P is population, ρ is the utility discount rate, U is the utility function and T is the time up to which the analysis is carried out.

The BGE for policy ω is then defined by solving[4]

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[4] Note that equation (7) in chapter 6 in the *Stern Review* defines the BGE as used by Stern *et al.* (2006, p. 185) and thus plays the same role as our equation (2). Unfortunately, equation (7) in the review contains a number of errors. It seems to use the utility function for $\eta \neq 1$, while the text before the equation and the definition of the welfare function in (6) assume $\eta=1$ (for which, in fact, (7) is not even defined). Second, it seems that $C_{BGE}+gt$ was assumed to be consumption at time t along a balanced growth path with growth rate g, whereas the correct formulation would have been $C_{BGE}\left(1+g\right)^{t}$. And finally, this wrong term for consumption at time t was then wrongly converted into utility by only putting C_{BGE} into the utility function and then adding gt to utility, although at this point it probably doesn't matter much anymore. While members of the Stern team in private confirmed these errors to us, we have not been able to find a publicly available erratum on this issue. We were privately assured that this error is only present in the printed document, and that for the calculations the correct equations were used, but as the source code of the BGE part of the modelling of the Stern team is not available, we cannot confirm this. We assume for the rest of the paper that these errors only appeared in print, not in the calculations, without having the certainty of looking at the source code we would have wished for and which should be the norm in scientific research.

$$(2) \qquad \sum_{t=0}^{T} U\left[\gamma(\omega)(1+\alpha)^{t}\right] P_t (1+\rho)^{-t} = W(\omega)$$

for *γ(ω)*, with *α* being a constant growth rate (that later drops out when changes in *γ* are calculated).

For a standard constant-relative-risk-aversion utility function

$$(3) \qquad U(C) = \begin{cases} C^{1-\eta}(1-\eta)^{-1} & \text{for } \eta \neq 1 \\ \ln C & \text{for } \eta = 1 \end{cases}$$

with *η* being the marginal elasticity of consumption, we have an explicit solution for *γ*

$$(4) \qquad \gamma(\omega) = \begin{cases} \left[(1-\eta)W(\omega)\right]^{\frac{1}{1-\eta}} \left[\sum_{t=0}^{T} \frac{(1+\alpha)^{t(1-\eta)} P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta \neq 1 \\ \exp\left(\frac{W(\omega) - \ln(1+\alpha)\sum_{t=0}^{T} t P_t (1+\rho)^{-t}}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) & \text{for } \eta = 1 \end{cases}$$

Defining the relative change in BGE for two policies *ω* and *ω'* as Δ*γ*, we get

$$(5) \qquad \Delta\gamma := \frac{\gamma(\omega') - \gamma(\omega)}{\gamma(\omega)} = \begin{cases} \left(\frac{W(\omega')}{W(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for} \eta \neq 1 \\ \exp\left(\frac{W(\omega') - W(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for } \eta = 1 \end{cases}$$

Note that Δ*γ* is independent of *α*, so that the change in BGE does not depend on the growth rate assumed in the calculation of a specific BGE – as long as the growth rates are the same for the two policy choices.

Note that population is (assumed to be) independent of the policy choice. If population is endogenous to the policy decision, one cannot use a welfare function like Equation (1). See Blackorby and Donaldson (1984) and Blackorby *et al*. (1995).

2.2. Uncertainty

We now treat *W*(*ω*, *s*) as a random variable where *p(s)* is the probability of state of the world *s*. Expected welfare then is

$$(6) \qquad \mathrm{E}W(\omega) = \sum_{p} p(\omega, s) \sum_{t=0}^{T} U\left(C_{\omega,s,t}\right) P_t (1+\rho)^{-t}$$

The certainty- and balanced growth equivalent (CBGE) is obtained be replacing *W(ω)* in (2) with expected welfare E*W(ω)* as defined in (6). The CBGE can then be solved as:

$$\text{(7)} \qquad \gamma_C(\omega) = \begin{cases} \left[(1-\eta)\mathrm{E}W(\omega)\right]^{\frac{1}{1-\eta}} \left[\sum\limits_{t=0}^{T} \dfrac{(1+\alpha)^{t(1-\eta)} P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta \neq 1 \\ \exp\left(\dfrac{\mathrm{E}W(\omega) - \ln(1+\alpha)\sum_{t=0}^{T} t P_t (1+\rho)^{-t}}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) & \text{for } \eta = 1 \end{cases}$$

The CBGE is the initial level of per capita consumption, which, if it grows without any uncertainty at some constant rate *α*, gives the same level of welfare as the expected welfare for some policy *ω* as defined in (6). It is a combination of the certainty equivalence ideas put forward by Rothschild and Stiglitz (1970) with the balanced growth equivalent of Mirrlees and Stern (1972).

The change in the CBGE equals:

$$\text{(8)} \qquad \Delta\gamma_C := \begin{cases} \left(\dfrac{\mathrm{E}W(\omega')}{\mathrm{E}W(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for } \eta \neq 1 \\ \exp\left(\dfrac{\mathrm{E}W(\omega') - \mathrm{E}W(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for } \eta = 1 \end{cases}$$

As before, the growth scenario *α* cancels.

2.3. Multiple regions

In the final step, we introduce multiple regions. Assuming that the global welfare function is utilitarian, we have

$$\text{(9)} \qquad W_R(\omega) = \sum_r \sum_{t=0}^{T} U\left(C_{\omega,t,r}\right) P_{t,r} (1+\rho)^{-t}$$

for a deterministic analysis and

$$\text{(10)} \qquad \mathrm{E}W_R(\omega) = \sum_p p(\omega,s) \sum_r \sum_{t=0}^{T} U\left(C_{\omega,s,t,r}\right) P_{t,r} (1+\rho)^{-t}$$

for an analysis with uncertainty. Per capita consumption *C* and population *P* are now fed into the welfare function for each region *r* individually.

Replacing *W(ω)* in (2) with the deterministic welfare function that is disaggregated by regions *W_R(ω)* gives the equity- and balanced growth equivalent (EBGE) for a specific policy choice. This solves as:

$$(11)\qquad \gamma_E(\omega)=\begin{cases}\left[(1-\eta)W_R(\omega)\right]^{\frac{1}{1-\eta}}\left[\sum_{t=0}^{T}\frac{(1+\alpha)^{t(1-\eta)}P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta\neq 1\\ \exp\left(\frac{W_R(\omega)-\ln(1+\alpha)\sum_{t=0}^{T}tP_t(1+\rho)^{-t}}{\sum_{t=0}^{T}P_t(1+\rho)^{-t}}\right) & \text{for } \eta=1\end{cases}$$

This combines a measure of inequality very much like Atkinson's (1970) with the BGE concept. The EBGE is the equally distributed (over the regions under consideration) initial per capita consumption, growing at a constant rate α that gives the same level of welfare as obtained for a specific policy choice ω from the welfare function defined in (9).

The certainty, equity- and balanced growth equivalent (CEBGE) follows by replacing *W(ω)* in (2) with the expected welfare from the regional disaggregated welfare function as defined in (10) for some policy choice ω. This solves as:

$$(12)\qquad \gamma_{CE}(\omega)=\begin{cases}\left[(1-\eta)\mathrm{E}W_R(\omega)\right]^{\frac{1}{1-\eta}}\left[\sum_{t=0}^{T}\frac{(1+\alpha)^{t(1-\eta)}P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta\neq 1\\ \exp\left(\frac{\mathrm{E}W_R(\omega)-\ln(1+\alpha)\sum_{t=0}^{T}tP_t(1+\rho)^{-t}}{\sum_{t=0}^{T}P_t(1+\rho)^{-t}}\right) & \text{for } \eta=1\end{cases}$$

which is the equally distributed (over the regions under consideration) initial per capita consumption growing without uncertainty at a constant rate α, that gives the same welfare level as the expected welfare of a certain policy choice ω as obtained by using (10).

From this it follows that the change in the EBGE between two policy options is

$$(13)\qquad \Delta\gamma_E:=\begin{cases}\left(\frac{W_R(\omega')}{W_R(\omega)}\right)^{\frac{1}{1-\eta}}-1 & \text{for } \eta\neq 1\\ \exp\left(\frac{W_R(\omega')-W_R(\omega)}{\sum_{t=0}^{T}P_t(1+\rho)^{-t}}\right)-1 & \text{for } \eta=1\end{cases}$$

And the change in the CEBGE between two policy options is

$$(14) \quad \Delta\gamma_{CE} := \begin{cases} \left(\dfrac{\mathrm{E}W_R(\omega')}{\mathrm{E}W_R(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for } \eta \neq 1 \\ \exp\left(\dfrac{\mathrm{E}W_R(\omega') - \mathrm{E}W_R(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for } \eta = 1 \end{cases}$$

Note that in Equation (14), the parameter η has a triple role. It is a measure of the curvature of the utility function – more specifically, the consumption elasticity of marginal utility – but it functions as the intertemporal substitution elasticity of consumption, the rate of risk aversion, and the rate of inequity aversion. Below, we refer to η as the rate of risk aversion.

Tol and Yohe (2007) show a similar derivation, but use the term certainty- and equity-equivalent *annuity* because Equation (5) – and hence (8), (13) and (14) – distribute the impact equally over time, as well as over states of the world and regions.

As stated in the introduction, we think that the *Stern Review* intended to report $\Delta\gamma_{CE}$ as defined in Equation (14), but they seem to report $\Delta\gamma$ (5) or $\Delta\gamma_C$ (8) instead.

3. The 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 modeled over 16 regions. Modeled 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 3.2, used in this paper, runs from 1950 to 2300 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 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 climate scenarios for the period 2010-2100 are 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, and the period 2100-2300 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 (2006a). 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 and population growth are perturbed by the effects of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. 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.

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 *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 (2002a; b) 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, 2002b).

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 3 times the per capita income (Tol, 1995; 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 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, 2002a). 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, 2002b).

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, 2002b).

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), heat-related disorders (with urbanization), and 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, 2002b).

In the Monte Carlo analyses, essentially all parameters are varied. The probability density functions are mostly based on expert guesses, but where possible “objective” estimates were used. Parameters are assumed to vary independently of one another. Details of the Monte Carlo analysis can be found on *FUND*'s website at http://www.fund-model.org.

4. Results

4.1. Scenarios

Stern *et al*. (2006) present the impacts of climate change as the change in BGE between a baseline scenario with no climate change impacts and various scenarios with climate impacts. We present similar results but add more sensitivity analysis. In particular, we present results for alternative assumptions on discounting and risk aversion, and include four alternative socio-economic scenarios. We refer to these runs as "costless mitigation". That is, we ran the model with a hypothetical policy ω, by which all climate change impacts are completely avoided, but none of the costs associated with such complete mitigation are accounted for. Comparing the change in the BGE between a run with a do-nothing policy (business as usual scenario) and the costless mitigation policy, we obtain a measure of the overall damage of climate change.

While these results are interesting, they are also difficult to interpret. Originally, the concept of a change in BGE was proposed to evaluate concrete policy proposals. Since completely mitigating all climate change impacts at no cost is impossible, looking at the change in BGE between a scenario with no climate change and various climate change scenarios cannot be considered as evaluating policy options. We therefore present a second set of results where we evaluate specific carbon taxation policies and calculate the change in BGE (or any of the more complicated concepts) from a business as usual scenario to a policy choice of some carbon taxation.

For any combination of socio economic scenario, pure rate of time preference, rate of risk aversion, uncertainty treatment and social welfare function, we calculated the BGE for two policy choices: One business as usual policy with no greenhouse gas taxation and the BGE for the optimal policy choice, in terms of the social welfare function employed. The latter is characterised as follows: Following Pigou (1947), we assumed that the optimal carbon tax should be the same for all agents at any time *t*, and that it has to increase with the interest rate (Hotelling, 1931). Given these constraints, the problem reduces to finding the optimal initial greenhouse gas tax level, i.e. the social shadow price of carbon emissions. The optimisations run for this paper use a simple search algorithm that finds a solution that is within \$0.50 of the true optimal tax value. Given the huge uncertainties of integrated assessment models and limited computational resources, this seemed a reasonable compromise.

In the following sections we point out our key findings both for the costless mitigation runs and the optimal policy runs.

4.2. Costless mitigation – total damage

Figure 1 shows the benefits of going from a business as usual policy to a costless mitigation policy in terms of change of CBGE for various pure rates of time preference, risk aversion and socio-economic scenario choices. Figure 1 shows the mean change in BGE over all socio-economic scenarios, with the minimum and maximum shown on the error bars. The numbers in this figure form the model sensitivity analysis to the results of the *Stern Review*.

In general, the numbers calculated by *FUND* tend to suggest lower total damages than the figures from the *Stern Review*, given apparently comparable welfare economic treatment. Probably the main driver for this effect is one crucial difference in modeling impacts in the model *PAGE* as used for the *Stern Review* and *FUND*: *PAGE* puts more emphasis on the negative impacts of climate change, i.e. it will never produce a net global benefit from an increase in temperature for any time step. *FUND* on the other hand has various sectors in which modest temperature increases in some regions can lead to net benefits, so that in particular in the earlier time periods impacts of climate change are positive for some regions. Furthermore, *PAGE* assumes that vulnerability to climate change is constant, while *FUND* has that regions grow less vulnerable as they grow richer. Sterner and Persson (2007) and Tol and Yohe (2007) show that this is an important assumption.

At the same time, our results mimic some key features of the *Stern Review* results: higher time preference rates and higher risk aversion always lead to lower impacts estimates. For time discounting, this is rather well established in the literature (e.g. Guo *et al.*, 2006; Newell and Pizer, 2003). That higher η values lead to lower damages is less straight forward, as it controls two effects at the same time. First, the effective discount rate is increased, which certainly leads to lower damage estimates. Second, more weight is given to unlikely but bad outcomes, i.e. the decision maker is assumed to be more risk averse, which should lead to higher damage estimates. The result from Figure 1 show that the first effect strongly dominates the second in the kind of uncertainty analysis employed for this paper, i.e. that the increase in the discount rate offsets the increase in risk aversion.

The *Stern Review* itself pointed out that a global welfare function cannot take into account how damages are distributed with respect to high/low income regions, and that a regional disaggregated welfare function would be a more appropriate choice. Figure 2 shows results using a social welfare function that is disaggregated into 16 world regions, again with the mean (and minimum and maximum) of the socio-economic scenarios for a costless mitigation policy.

There are three key insights: First, using a disaggregated regional social welfare function always increases total damage estimates; second, the role of η is reversed; and third, high η values lead to estimates that are very large.

The first result, i.e. higher damages from a regional disaggregated welfare function, is not theoretically unambiguous, but nevertheless it is robust over all scenarios analyzed for this paper. A disaggregated regional welfare function in general gives higher weights to impacts in poor regions than in high income regions. In general (but not in every detail), *FUND* has more negative impacts in poor regions.

With a regional welfare function, η plays a third role, namely that of inequality aversion, in addition to the parameter of risk aversion and substitution of consumption over time. With this third role added, the response of the total damage estimates to higher values for η is reversed, in particular the inequality and risk aversion aspect dominate the higher discount rate aspect of high η values and therefore total damage estimates increase with higher values for η. This directly points to one central problem with the kind of welfare function commonly employed in climate change analysis (and this paper), namely the over use of η to control three issues at the same time (cf. Beckerman and Hepburn, 2007). A number of the critics of the *Stern Review* (e.g., Dasgupta, 2007) have argued that while a low pure rate of time preference might be acceptable, one should pick a higher value for η, so that the overall discount rate is more in line with market interest rates. In the context of a global welfare function as used by Stern *et al*. (2006) this suggestion makes sense, but with a regional welfare function the effect on the estimated damage may be unexpected.

Finally, we produce very large results for high η values with a regional welfare function. This is a direct manifestation of Weitzman's (2008) fat tail argument: Comparing the regional probabilistic results with deterministic runs, and a detailed analysis of the drivers of those extreme values shows that some regions approach very low consumption levels in some scenarios in our Monte Carlo analysis. With a global welfare function those extreme results in a few regions are averaged out, but with a regional welfare function these fat tails in single regions drive the analysis.

4.3. Optimal mitigation

While an analysis of the total expected damage of climate change is of interest, a more policy relevant question is that of the optimal response and of the maximal achievable improvement over a business as usual policy.

Table 1 compares the total damage with the maximum improvement possible via mitigation for SRES scenario A2 for a probabilistic analysis. The A2 scenario is the scenario of choice in the *Stern Review*. For a global welfare function as used by the *Stern Review*, the best possible improvement is always significantly lower than the total damage estimate. Except for runs with high η values, this conclusion also holds for a regional welfare function. The runs with η=2 have to be interpreted with care, since the manifestation of fat-tails showing up there might make the framework used to look for the optimal policy response less appropriate.

A global welfare function underestimates by a large margin the improvements that can be obtained by an optimal policy choice. Table 2 compares the optimal carbon tax levels in the year 2000 for the A2 scenario. While the optimal initial tax is higher for a regional welfare function, the change in the BGE for a regional welfare function is much larger for the optimal policy than the change in the tax level. The prime reason for this is that the introduction of a regional welfare function not only gives more weight to damages in low income regions, but mitigation costs in poor regions also get a higher weight, thereby balancing the effect of the regional welfare function somewhat.

Table 3 highlights the importance of distributional issues and uncertainty in climate change. Table 3 shows our estimate of the total impacts of climate change using a global welfare function ignoring uncertainty and compares this to the regional welfare function. In the global welfare function, global average impacts are computed before being converted to utility. In the regional welfare function, regional average impacts are converted to utility and then averaged for the world. Irrespective of the rates of pure time preference or risk aversion, the regional welfare function implies impacts that are substantially higher. This is well-known in the literature (Azar and Sterner, 1996; Fankhauser *et al.*, 1997; 1998; Azar, 1999). It is remarkable that the *Stern Review* overlooked this. With uncertainty, the difference between a global and a regional welfare function is even stronger.

Qualitatively, the results for the A2 scenario hold for the other scenarios as well. See the Appendix for detailed results. Quantitatively, the results are different, of course, and where the relationship is ambiguous (e.g., between η and $\Delta\gamma$), different scenarios may show different signs. Table 4 shows the total impact of climate change for five alternative socio-economic and emissions scenarios. The A2 scenario is generally in the middle of the range. Hotter (FUND) and poorer (B2) scenarios show higher impacts, while cooler (B1) and richer (A1b) scenarios show lower impacts.

5. Conclusion

This paper defines various balanced growth equivalences, and applies them to compute the impacts of climate change and the benefits of emission reduction with the integrated assessment model *FUND*. We conduct a wider sensitivity analysis than run by the *Stern Review.* We find that the impacts of climate change are sensitive to the pure rate of time preference, the rate of risk aversion, the level of spatial disaggregation, the inclusion of uncertainty, and the socio-economic scenario. Our results span a wider range in both directions compared to the *Stern Review*, thereby questioning the assertion that the high results obtained by the *Stern Review* are robust. We find that the guess of the *Stern Review* that a regional welfare function might increase overall damage estimates by a quarter (Stern *et al.*, 2006, p. 187) is very conservative. In our runs, the introduction of a regional welfare function, in particular in combination with a high risk aversion, has a much larger effect on the results. Finally, we show that the *Stern Review* was wrong to equate the impact of climate change and the benefits of emission reduction. Qualitatively, this was known. Quantitatively, we show that this is a big mistake.

The results also show areas that need more research work. This includes improved socio-economic and climate scenarios, and better and more complete estimates of the impacts of climate change. In particular, disentangling intertemporal substitution from risk aversion and inequality aversion is a high priority (e.g., Carlsson *et al.*, 2005). With only one parameter to control three important effects, as commonly used in climate policy analysis, model- and scenario-specific ambiguities emerge. The fat tails that showed up in some of our results with high risk aversion and a regional welfare function are another area for further research.

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Figures

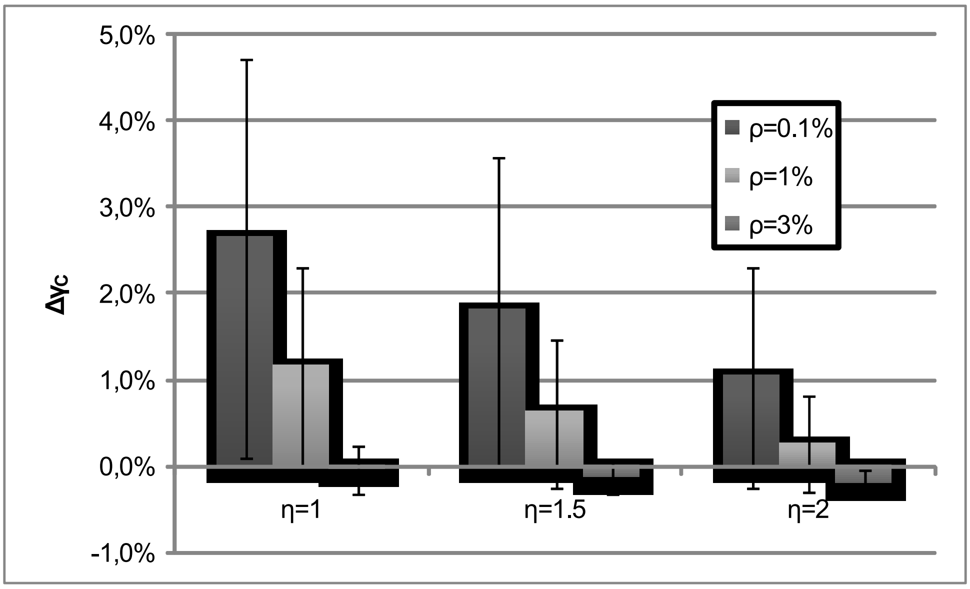

Figure 1: Costless mitigation with a global welfare function

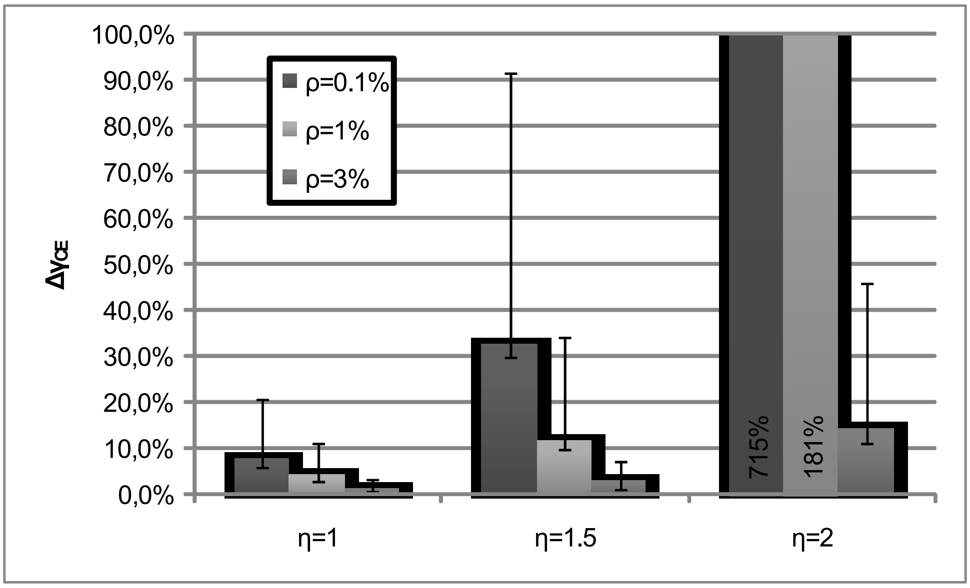

Figure 2: Costless mitigation with a regional welfare function

Tables

	$\eta=1.0$	**$\eta=1.5$**	**$\eta=2.0$**
Global welfare function			
$\varrho=0.1\%$	1.35% (3.38%)	0.85% (2.46%)	0.40% (1.52%)
$\varrho=1.0\%$	0.40% (1.57%)	0.19% (0.93%)	0.08% (0.46%)
$\varrho=3.0\%$	0.01% (0.03%)	0.02% (-0.07%)	0.01% (-0.14%)
Regional welfare function			
$\varrho=0.1\%$	4.46% (10.18%)	38.62% (48.38%)	1019.24% (1100.72%)
$\varrho=1.0\%$	1.54% (5.39%)	10.79% (16.21%)	239.87% (258.57%)
$\varrho=3.0\%$	0.08% (1.59%)	0.61% (3.41%)	11.42% (15.91%)

Table 1: Change in CBGE and CEBGE for optimal (costless in brackets) mitigation policy for SRES scenario A2

	η=1.0	**η=1.5**	**η=2.0**
Global welfare function			
ρ=0.1%	40.63	23.75	11.88
ρ=1.0%	15.63	6.88	3.13
ρ=3.0%	0.63	0.63	0.63
Regional welfare function			
ρ=0.1%	51.25	54.38	50.63
ρ=1.0%	21.25	25.63	31.25
ρ=3.0%	2.50	6.88	7.50

Table 2: Optimal initial tax ($/tC) for SRES A2 scenario under a probabilistic analysis

	η=1.0	**η=1.5**	**η=2.0**
Global welfare function			
ρ=0.1%	1.56%	0.59%	-0.15%
ρ=1.0%	0.07%	-0.46%	-0.75%
ρ=3.0%	-0.91%	-0.94%	-0.95%
Regional welfare function			
ρ=0.1%	3.15%	2.74%	2.54%
ρ=1.0%	1.07%	1.22%	1.75%
ρ=3.0%	-0.51%	0.40%	1.44%

Table 3: Change in BGE and EBGE for costless mitigation policy for SRES scenario A2 without uncertainty

	$\eta=1.0$			$\eta=1.5$			$\eta=2.0$		
	$\rho=0.1$%	$\rho=1.0$%	$\rho=3.0$%	$\rho=0.1$%	$\rho=1.0$%	$\rho=3.0$%	$\rho=0.1$%	$\rho=1.0$%	$\rho=3.0$%
Global welfare function									
FUND	4.72%	2.30%	0.23%	3.58%	1.47%	0.06%	2.29%	0.80%	-0.05%
A1b	1.51%	0.50%	-0.20%	0.56%	0.02%	-0.28%	-0.01%	-0.21%	-0.32%
A2	3.38%	1.57%	0.03%	2.46%	0.93%	-0.07%	1.52%	0.46%	-0.14%
B1	0.09%	-0.16%	-0.32%	-0.13%	-0.26%	-0.33%	-0.25%	-0.30%	-0.33%
B2	3.54%	1.59%	-0.01%	2.65%	0.98%	-0.11%	1.69%	0.50%	-0.19%
Regional welfare function									
FUND	12.74%	6.89%	1.93%	59.38%	22.37%	4.32%	1277%	368.7%	31.93%
A1b	5.07%	2.61%	0.95%	17.46%	5.68%	2.01%	407.1%	80.80%	6.07%
A2	10.18%	5.39%	1.59%	48.38%	16.21%	3.41%	1100%	258.5%	15.91%
B1	1.96%	1.23%	0.70%	2.45%	2.02%	1.80%	3.54%	3.14%	3.09%
B2	9.11%	4.67%	1.42%	34.41%	12.39%	3.13%	788.5%	192.6%	13.63%

Table 4: Costless mitigation for probabilistic runs by socio economic scenario

Appendix – Complete results

Global probabilistic welfare function

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	4.72%	3.58%	2.29%
1.0%	2.30%	1.47%	0.80%
3.0%	0.23%	0.06%	-0.05%
SRES A1b			
0.1%	1.51%	0.56%	-0.01%
1.0%	0.50%	0.02%	-0.21%
3.0%	-0.20%	-0.28%	-0.32%
SRES A2			
0.1%	3.38%	2.46%	1.52%
1.0%	1.57%	0.93%	0.46%
3.0%	0.03%	-0.07%	-0.14%
SRES B1			
0.1%	0.09%	-0.13%	-0.25%
1.0%	-0.16%	-0.26%	-0.30%
3.0%	-0.32%	-0.33%	-0.33%
SRES B2			
0.1%	3.54%	2.65%	1.69%
1.0%	1.59%	0.98%	0.50%
3.0%	-0.01%	-0.11%	-0.19%

Table 5: $\Delta\gamma_C$ between a BAU scenario and a costless, full mitigation scenario for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	2.22%	1.55%	0.87%
1.0%	0.77%	0.44%	0.21%
3.0%	0.03%	0.03%	0.02%
SRES A1b			
0.1%	0.33%	0.09%	0.02%
1.0%	0.05%	0.03%	0.01%
3.0%	0.00%	0.01%	0.01%
SRES A2			
0.1%	1.35%	0.85%	0.40%
1.0%	0.40%	0.19%	0.08%
3.0%	0.01%	0.02%	0.01%
SRES B1			
0.1%	0.03%	0.02%	0.01%
1.0%	0.01%	0.01%	0.00%
3.0%	0.00%	0.00%	0.00%
SRES B2			
0.1%	1.35%	0.92%	0.47%
1.0%	0.38%	0.21%	0.10%
3.0%	0.01%	0.02%	0.01%

Table 6: $\Delta\gamma_C$ between a BAU scenario and the optimal mitigation strategy for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	$43.13	$26.88	$15.00
1.0%	$20.00	$10.63	$5.00
3.0%	$1.25	$0.63	$0.63
SRES A1b			
0.1%	$16.88	$2.50	$0.63
1.0%	$3.75	$0.63	$0.63
3.0%	$0.63	$0.63	$0.63
SRES A2			
0.1%	$40.63	$23.75	$11.88
1.0%	$15.63	$6.88	$3.13
3.0%	$0.63	$0.63	$0.63
SRES B1			
0.1%	$7.50	$2.50	$0.63
1.0%	$2.50	$0.63	$0.63
3.0%	$0.63	$0.00	$0.00
SRES B2			
0.1%	$41.88	$25.00	$13.13
1.0%	$16.88	$8.13	$3.75
3.0%	$0.63	$0.63	$0.63

Table 7: Optimal global tax per ton of carbon emission in the year 2000

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%			
Expected temp in 2050	1.97°	1.99°	2.00°
Expected temp in 2100	3.08°	3.17°	3.27°
Max. expected temp	4.72°	4.71°	4.77°
1.0%			
Expected temp in 2050	2.00°	2.01°	2.02°
Expected temp in 2100	3.26°	3.35°	3.43°
Max. expected temp	4.89°	4.97°	5.12°
3.0%			
Expected temp in 2050	2.03°	2.03°	2.03°
Expected temp in 2100	3.53°	3.54°	3.53°
Max. expected temp	5.83°	5.79°	5.30°
SRES A1b			
0.1%			
Expected temp in 2050	2.10°	2.13°	2.13°
Expected temp in 2100	3.42°	3.54°	3.57°
Max. expected temp	5.79°	6.22°	6.05°
1.0%			
Expected temp in 2050	2.13°	2.13°	2.13°
Expected temp in 2100	3.53°	3.57°	3.56°
Max. expected temp	6.15°	6.22°	5.48°
3.0%			
Expected temp in 2050	2.13°	2.13°	2.13°
Expected temp in 2100	3.56°	3.55°	3.50°
Max. expected temp	5.70°	5.20°	4.84°
SRES A2			
0.1%			
Expected temp in 2050	1.96°	1.98°	1.99°
Expected temp in 2100	3.08°	3.17°	3.25°
Max. expected temp	5.47°	5.49°	5.59°
1.0%			
Expected temp in 2050	1.99°	2.00°	2.01°
Expected temp in 2100	3.23°	3.30°	3.33°
Max. expected temp	5.63°	5.80°	5.86°
3.0%			
Expected temp in 2050	2.01°	2.01°	2.01°
Expected temp in 2100	3.37°	3.36°	3.36°
Max. expected temp	6.25°	5.76°	5.34°
SRES B1			
0.1%			
Expected temp in 2050	2.04°	2.05°	2.05°

Expected temp in 2100	3.10°	3.12°	3.13°
Max. expected temp	4.59°	4.59°	4.59°
1.0%			
Expected temp in 2050	2.05°	2.05°	2.05°
Expected temp in 2100	3.12°	3.13°	3.13°
Max. expected temp	4.59°	4.59°	4.35°
3.0%			
Expected temp in 2050	2.05°	2.06°	2.06°
Expected temp in 2100	3.13°	3.15°	3.15°
Max. expected temp	4.34°	4.76°	4.76°
SRES B2			
0.1%			
Expected temp in 2050	1.98°	2.00°	2.02°
Expected temp in 2100	3.03°	3.11°	3.20°
Max. expected temp	4.89°	4.87°	4.91°
1.0%			
Expected temp in 2050	2.01°	2.03°	2.04°
Expected temp in 2100	3.19°	3.26°	3.30°
Max. expected temp	5.04°	5.11°	5.17°
3.0%			
Expected temp in 2050	2.05°	2.04°	2.04°
Expected temp in 2100	3.35°	3.34°	3.34°
Max. expected temp	5.70°	5.28°	4.93°

Table 8: Expected temperature changes relative to 1990 for the optimal mitigation strategy for a global welfare function for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η) for the year 2050 and 2100 and the maximum expected temperature change for the whole simulation period 2000-2300

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%			
Expected RF in 2050	4.82	4.93	5.04
Expected RF in 2100	6.11	6.33	6.64
Max. expected RF	6.73	6.73	6.89
1.0%			
Expected RF in 2050	5.00	5.09	5.16
Expected RF in 2100	6.67	6.98	7.30
Max. expected RF	7.07	7.28	7.61
3.0%			
Expected RF in 2050	5.22	5.24	5.23
Expected RF in 2100	7.86	7.90	7.74
Max. expected RF	8.84	8.83	8.17
SRES A1b			
0.1%			
Expected RF in 2050	5.45	5.61	5.64
Expected RF in 2100	6.83	7.23	7.30
Max. expected RF	8.36	8.89	8.56
1.0%			
Expected RF in 2050	5.60	5.64	5.63
Expected RF in 2100	7.20	7.31	7.24
Max. expected RF	8.74	8.82	7.88
3.0%			
Expected RF in 2050	5.64	5.63	5.62
Expected RF in 2100	7.29	7.17	6.89
Max. expected RF	8.17	7.58	7.15
SRES A2			
0.1%			
Expected RF in 2050	4.76	4.87	4.96
Expected RF in 2100	6.18	6.50	6.80
Max. expected RF	7.94	7.82	7.88
1.0%			
Expected RF in 2050	4.93	5.00	5.04
Expected RF in 2100	6.74	7.00	7.13
Max. expected RF	7.96	8.23	8.40
3.0%			
Expected RF in 2050	5.07	5.07	5.07
Expected RF in 2100	7.27	7.25	7.19
Max. expected RF	9.14	8.50	7.95
SRES B1			
0.1%			
Expected RF in 2050	5.09	5.13	5.15

Expected RF in 2100	5.78	5.84	5.88
Max. expected RF	6.57	6.55	6.52
1.0%			
Expected RF in 2050	5.13	5.15	5.15
Expected RF in 2100	5.85	5.88	5.87
Max. expected RF	6.53	6.49	6.18
3.0%			
Expected RF in 2050	5.15	5.17	5.17
Expected RF in 2100	5.87	5.93	5.93
Max. expected RF	6.17	6.84	6.84
SRES B2			
0.1%			
Expected RF in 2050	4.83	4.94	5.04
Expected RF in 2100	5.85	6.09	6.35
Max. expected RF	7.01	6.89	6.92
1.0%			
Expected RF in 2050	5.02	5.10	5.15
Expected RF in 2100	6.39	6.61	6.75
Max. expected RF	7.10	7.26	7.45
3.0%			
Expected RF in 2050	5.19	5.19	5.19
Expected RF in 2100	6.97	6.94	6.88
Max. expected RF	8.33	7.82	7.37

Table 9: Expected radiative forcing for the optimal mitigation strategy for a global welfare function for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η) for the year 2050 and 2100 and the maximum expected radiative forcing for the whole simulation period 2000-2300

Global deterministic welfare function

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	2.35%	1.15%	0.21%
1.0%	0.56%	-0.12%	-0.51%
3.0%	-0.70%	-0.77%	-0.80%
SRES A1b			
0.1%	-0.20%	-0.75%	-0.95%
1.0%	-0.74%	-0.95%	-0.99%
3.0%	-1.00%	-0.99%	-0.95%
SRES A2			
0.1%	1.56%	0.59%	-0.15%
1.0%	0.07%	-0.46%	-0.75%
3.0%	-0.91%	-0.94%	-0.95%
SRES B1			
0.1%	-0.91%	-1.03%	-1.04%
1.0%	-1.06%	-1.06%	-1.02%
3.0%	-1.04%	-0.99%	-0.94%
SRES B2			
0.1%	1.50%	0.55%	-0.17%
1.0%	-0.01%	-0.50%	-0.78%
3.0%	-0.96%	-0.99%	-0.99%

Table 10: $\Delta\gamma$ between a BAU scenario and a costless, full mitigation scenario for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	1.82%	0.93%	0.36%
1.0%	0.57%	0.21%	0.07%
3.0%	0.02%	0.00%	0.00%
SRES A1b			
0.1%	0.14%	0.02%	0.00%
1.0%	0.02%	0.00%	0.00%
3.0%	0.00%	0.00%	0.00%
SRES A2			
0.1%	1.19%	0.57%	0.20%
1.0%	0.30%	0.09%	0.02%
3.0%	0.00%	0.00%	0.00%
SRES B1			
0.1%	0.03%	0.01%	0.00%
1.0%	0.01%	0.00%	0.00%
3.0%	0.00%	0.00%	0.00%
SRES B2			
0.1%	1.15%	0.56%	0.21%
1.0%	0.28%	0.09%	0.03%
3.0%	0.01%	0.00%	0.00%

Table 11: $\Delta\gamma$ between a BAU scenario and the optimal mitigation strategy for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	$41.25	$20.63	$8.75
1.0%	$16.88	$6.25	$1.88
3.0%	$0.63	$0.63	$0.00
SRES A1b			
0.1%	$10.63	$1.25	$0.00
1.0%	$2.50	$0.00	$0.00
3.0%	$0.00	$0.00	$0.00
SRES A2			
0.1%	$41.25	$21.88	$8.75
1.0%	$14.38	$5.00	$1.25
3.0%	$0.63	$0.00	$0.00
SRES B1			
0.1%	$6.88	$2.50	$0.63
1.0%	$2.50	$0.63	$0.00
3.0%	$0.00	$0.00	$0.00
SRES B2			
0.1%	$40.63	$21.88	$8.75
1.0%	$14.38	$5.00	$1.25
3.0%	$0.63	$0.00	$0.00

Table 12: Optimal global tax per ton of carbon emission in the year 2000

Regional probabilistic Welfare Function

	η		
ρ	1.0	1.5	2.0
FUND			
0.1%	12.74%	59.38%	1277.47%
1.0%	6.89%	22.37%	368.71%
3.0%	1.93%	4.32%	31.93%
SRES A1b			
0.1%	5.07%	17.46%	407.12%
1.0%	2.61%	5.68%	80.80%
3.0%	0.95%	2.01%	6.07%
SRES A2			
0.1%	10.18%	48.38%	1100.72%
1.0%	5.39%	16.21%	258.57%
3.0%	1.59%	3.41%	15.91%
SRES B1			
0.1%	1.96%	2.45%	3.54%
1.0%	1.23%	2.02%	3.14%
3.0%	0.70%	1.80%	3.09%
SRES B2			
0.1%	9.11%	34.41%	788.49%
1.0%	4.67%	12.39%	192.59%
3.0%	1.42%	3.13%	13.63%

Table 13: $\Delta\gamma_{CE}$ between a BAU scenario and a costless, full mitigation scenario for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	6.47%	49.74%	1198.46%
1.0%	2.70%	17.10%	347.00%
3.0%	0.23%	1.56%	27.06%
SRES A1b			
0.1%	1.07%	13.04%	389.04%
1.0%	0.25%	2.98%	75.09%
3.0%	0.01%	0.11%	2.91%
SRES A2			
0.1%	4.46%	38.62%	1019.24%
1.0%	1.54%	10.79%	239.87%
3.0%	0.08%	0.61%	11.42%
SRES B1			
0.1%	0.11%	0.11%	0.40%
1.0%	0.04%	0.04%	0.09%
3.0%	0.00%	0.01%	0.03%
SRES B2			
0.1%	3.94%	27.02%	738.24%
1.0%	1.28%	7.97%	179.19%
3.0%	0.07%	0.48%	9.15%

Table 14: $\Delta\gamma_{CE}$ between a BAU scenario and the optimal mitigation strategy for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	$49.38	$50.00	$43.13
1.0%	$24.38	$26.25	$25.63
3.0%	$3.75	$5.63	$6.88
SRES A1b			
0.1%	$26.25	$20.00	$9.38
1.0%	$8.13	$9.38	$6.25
3.0%	$1.25	$2.50	$2.50
SRES A2			
0.1%	$51.25	$54.38	$50.63
1.0%	$21.25	$25.63	$31.25
3.0%	$2.50	$6.88	$7.50
SRES B1			
0.1%	$10.63	$4.38	$2.50
1.0%	$5.00	$2.50	$1.25
3.0%	$0.63	$1.25	$1.25
SRES B2			
0.1%	$46.25	$40.00	$33.75
1.0%	$21.88	$21.25	$18.75
3.0%	$2.50	$4.38	$4.38

Table 15: Optimal global tax per ton of carbon emission in the year 2000

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%			
Expected temp in 2050	1.96°	1.94°	1.94°
Expected temp in 2100	3.01°	2.87°	2.83°
Max. expected temp	4.55°	4.03°	3.72°
1.0%			
Expected temp in 2050	1.99°	1.98°	1.97°
Expected temp in 2100	3.18°	3.02°	2.91°
Max. expected temp	4.66°	4.05°	3.69°
3.0%			
Expected temp in 2050	2.03°	2.02°	2.01°
Expected temp in 2100	3.43°	3.26°	3.09°
Max. expected temp	4.94°	4.20°	3.80°
SRES A1b			
0.1%			
Expected temp in 2050	2.08°	2.08°	2.11°
Expected temp in 2100	3.31°	3.23°	3.30°
Max. expected temp	5.31°	4.58°	4.53°
1.0%			
Expected temp in 2050	2.12°	2.11°	2.11°
Expected temp in 2100	3.48°	3.35°	3.30°
Max. expected temp	5.57°	4.69°	4.47°
3.0%			
Expected temp in 2050	2.13°	2.13°	2.12°
Expected temp in 2100	3.55°	3.43°	3.30°
Max. expected temp	5.42°	4.70°	4.40°
SRES A2			
0.1%			
Expected temp in 2050	1.94°	1.93°	1.93°
Expected temp in 2100	2.98°	2.85°	2.80°
Max. expected temp	5.12°	4.44°	3.98°
1.0%			
Expected temp in 2050	1.98°	1.97°	1.95°
Expected temp in 2100	3.17°	3.04°	2.88°
Max. expected temp	5.24°	4.40°	3.86°
3.0%			
Expected temp in 2050	2.01°	1.99°	1.99°
Expected temp in 2100	3.33°	3.16°	3.07°
Max. expected temp	5.31°	4.26°	3.99°
SRES B1			
0.1%			
Expected temp in 2050	2.04°	2.05°	2.05°

Expected temp in 2100	3.08°	3.10°	3.11°
Max. expected temp	4.53°	4.50°	4.32°
1.0%			
Expected temp in 2050	2.05°	2.05°	2.05°
Expected temp in 2100	3.10°	3.11°	3.12°
Max. expected temp	4.48°	4.34°	4.23°
3.0%			
Expected temp in 2050	2.05°	2.05°	2.05°
Expected temp in 2100	3.13°	3.11°	3.09°
Max. expected temp	4.34°	4.06°	3.91°
SRES B2			
0.1%			
Expected temp in 2050	1.97°	1.97°	1.98°
Expected temp in 2100	2.99°	2.94°	2.90°
Max. expected temp	4.76°	4.34°	3.96°
1.0%			
Expected temp in 2050	2.01°	2.00°	2.00°
Expected temp in 2100	3.14°	3.06°	3.00°
Max. expected temp	4.75°	4.20°	3.91°
3.0%			
Expected temp in 2050	2.04°	2.03°	2.03°
Expected temp in 2100	3.31°	3.22°	3.15°
Max. expected temp	4.91°	4.24°	3.98°

Table 16: Expected temperature changes relative to 1990 for the optimal mitigation strategy for a regional welfare function for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η) for the year 2050 and 2100 and the maximum expected temperature change for the whole simulation period 2000-2300

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%			
Expected RF in 2050	4.76	4.61	4.59
Expected RF in 2100	5.88	5.39	5.16
Max. expected RF	6.48	5.72	5.34
1.0%			
Expected RF in 2050	4.95	4.85	4.77
Expected RF in 2100	6.36	5.71	5.29
Max. expected RF	6.70	5.85	5.41
3.0%			
Expected RF in 2050	5.17	5.11	5.04
Expected RF in 2100	7.27	6.33	5.64
Max. expected RF	7.47	6.37	5.78
SRES A1b			
0.1%			
Expected RF in 2050	5.34	5.31	5.44
Expected RF in 2100	6.47	6.09	6.18
Max. expected RF	7.64	6.64	6.65
1.0%			
Expected RF in 2050	5.53	5.47	5.47
Expected RF in 2100	6.99	6.44	6.12
Max. expected RF	7.89	6.85	6.61
3.0%			
Expected RF in 2050	5.62	5.57	5.53
Expected RF in 2100	7.21	6.61	5.95
Max. expected RF	7.82	6.94	6.57
SRES A2			
0.1%			
Expected RF in 2050	4.69	4.57	4.53
Expected RF in 2100	5.82	5.37	5.16
Max. expected RF	7.45	6.32	5.69
1.0%			
Expected RF in 2050	4.88	4.81	4.67
Expected RF in 2100	6.47	5.86	5.26
Max. expected RF	7.39	6.28	5.64
3.0%			
Expected RF in 2050	5.04	4.96	4.93
Expected RF in 2100	7.07	6.16	5.72
Max. expected RF	7.79	6.32	5.96
SRES B1			
0.1%			
Expected RF in 2050	5.06	5.11	5.12

Expected RF in 2100	5.74	5.80	5.80
Max. expected RF	6.49	6.40	6.13
1.0%			
Expected RF in 2050	5.10	5.12	5.13
Expected RF in 2100	5.80	5.82	5.82
Max. expected RF	6.34	6.15	6.06
3.0%			
Expected RF in 2050	5.15	5.13	5.12
Expected RF in 2100	5.87	5.77	5.65
Max. expected RF	6.17	5.93	5.81
SRES B2			
0.1%			
Expected RF in 2050	4.79	4.76	4.75
Expected RF in 2100	5.70	5.49	5.32
Max. expected RF	6.83	6.14	5.64
1.0%			
Expected RF in 2050	4.96	4.93	4.90
Expected RF in 2100	6.16	5.79	5.54
Max. expected RF	6.69	6.02	5.71
3.0%			
Expected RF in 2050	5.16	5.11	5.10
Expected RF in 2100	6.78	6.29	5.93
Max. expected RF	7.26	6.35	6.02

Table 17: Expected radiative forcing for the optimal mitigation strategy for a regional welfare function for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η) for the year 2050 and 2100 and the maximum expected radiative forcing for the whole simulation period 2000-2300

Regional deterministic welfare function

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	3.81%	2.81%	2.23%
1.0%	1.53%	1.29%	1.62%
3.0%	-0.33%	0.45%	1.39%
SRES A1b			
0.1%	1.09%	0.88%	1.22%
1.0%	0.15%	0.42%	1.14%
3.0%	-0.54%	0.20%	1.16%
SRES A2			
0.1%	3.15%	2.74%	2.54%
1.0%	1.07%	1.22%	1.75%
3.0%	-0.51%	0.40%	1.44%
SRES B1			
0.1%	0.05%	0.37%	1.06%
1.0%	-0.38%	0.20%	1.06%
3.0%	-0.69%	0.14%	1.14%
SRES B2			
0.1%	2.67%	2.30%	2.32%
1.0%	0.86%	1.09%	1.81%
3.0%	-0.44%	0.52%	1.70%

Table 18: $\Delta\gamma_E$ between a BAU scenario and a costless, full mitigation scenario for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	1.56%	0.65%	0.20%
1.0%	0.48%	0.14%	0.04%
3.0%	0.02%	0.00%	0.00%
SRES A1b			
0.1%	0.13%	0.02%	0.00%
1.0%	0.03%	0.00%	0.00%
3.0%	0.00%	0.00%	0.00%
SRES A2			
0.1%	1.28%	0.57%	0.19%
1.0%	0.31%	0.09%	0.03%
3.0%	0.00%	0.00%	0.00%
SRES B1			
0.1%	0.03%	0.01%	0.00%
1.0%	0.01%	0.00%	0.00%
3.0%	0.00%	0.00%	0.00%
SRES B2			
0.1%	1.04%	0.44%	0.14%
1.0%	0.24%	0.07%	0.02%
3.0%	0.00%	0.00%	0.00%

Table 19: $\Delta\gamma_E$ between a BAU scenario and the optimal mitigation strategy for various socio economic scenarios, pure rate of time preference values (ρ) and marginal elasticity of consumption values (η)

	η		
ρ	**1.0**	**1.5**	**2.0**
FUND			
0.1%	$32.50	$15.00	$6.25
1.0%	$13.13	$4.38	$1.88
3.0%	$0.63	$0.63	$0.00
SRES A1b			
0.1%	$7.50	$1.25	$0.00
1.0%	$1.25	$0.00	$0.00
3.0%	$0.00	$0.00	$0.00
SRES A2			
0.1%	$33.13	$15.63	$5.63
1.0%	$11.25	$3.13	$1.25
3.0%	$0.63	$0.00	$0.00
SRES B1			
0.1%	$6.25	$2.50	$0.63
1.0%	$2.50	$0.63	$0.63
3.0%	$0.63	$0.00	$0.00
SRES B2			
0.1%	$33.13	$15.00	$5.63
1.0%	$10.63	$3.13	$1.25
3.0%	$0.63	$0.00	$0.00

Table 20: Optimal global tax per ton of carbon emission in the year 2000

Year	**Number**	**Title/Author(s)** **ESRI Authors/Co-authors *Italicised***
2008	227	Changing Returns to Education During a Boom? The Case of Ireland *Seamus McGuinness, Frances McGinnity, Philip O'Connell*
	226	'New' and 'Old' Social Risks: Life Cycle and Social Class Perspectives on Social Exclusion in Ireland *Christopher T. Whelan* and *Bertrand Maître*
	225	The Climate Preferences of Irish Tourists by Purpose of Travel *Seán Lyons, Karen Mayor* and *Richard S.J. Tol*
	224	A Hirsch Measure for the Quality of Research Supervision, and an Illustration with Trade Economists *Frances P. Ruane* and *Richard S.J. Tol*
	223	Environmental Accounts for the Republic of Ireland: 1990-2005 *Seán Lyons, Karen Mayor* and *Richard S.J. Tol*
2007	222	Assessing Vulnerability of Selected Sectors under Environmental Tax Reform: The issue of pricing power *J. Fitz Gerald, M. Keeney and S. Scott*
	221	Climate Policy Versus Development Aid *Richard S.J. Tol*
	220	Exports and Productivity – Comparable Evidence for 14 Countries The International Study Group on Exports and Productivity
	219	Energy-Using Appliances and Energy-Saving Features: Determinants of Ownership in Ireland *Joe O'Doherty, Seán Lyons* and *Richard S.J. Tol*
	218	The Public/Private Mix in Irish Acute Public Hospitals: Trends and Implications *Jacqueline O'Reilly* and *Miriam M. Wiley*
	217	Regret About the Timing of First Sexual Intercourse: The Role of Age and Context *Richard Layte*, Hannah McGee

216	Determinants of Water Connection Type and Ownership of Water-Using Appliances in Ireland *Joe O'Doherty, Seán Lyons* and *Richard S.J. Tol*
215	Unemployment – Stage or Stigma? Being Unemployed During an Economic Boom *Emer Smyth*
214	The Value of Lost Load *Richard S.J. Tol*
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212	Acting Up or Opting Out? Truancy in Irish Secondary Schools *Merike Darmody, Emer Smyth* and *Selina McCoy*
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210	Holiday Destinations: Understanding the Travel Choices of Irish Tourists *Seán Lyons, Karen Mayor* and *Richard S.J. Tol*
209	The Effectiveness of Competition Policy and the Price-Cost Margin: Evidence from Panel Data Patrick McCloughan, *Seán Lyons* and William Batt
208	Tax Structure and Female Labour Market Participation: Evidence from Ireland *Tim Callan,* A. Van Soest, *J.R. Walsh*
207	Distributional Effects of Public Education Transfers in Seven European Countries *Tim Callan,* Tim Smeeding and Panos Tsakloglou
206	The Earnings of Immigrants in Ireland: Results from the 2005 EU Survey of Income and Living Conditions *Alan Barrett* and *Yvonne McCarthy*
205	Convergence of Consumption Patterns During Macroeconomic Transition: A Model of Demand in Ireland and the OECD *Seán Lyons, Karen Mayor* and *Richard S.J. Tol*