Risk Aversion, Time Preference, and the Social Cost of Carbon

David Anthoff[a,b], Richard S.J. Tol[a,c,d,e] and Gary W. Yohe[f]

Abstract: The Stern Review reported a social cost of carbon of over $300/tC, calling for ambitious climate policy. We here conduct a systematic sensitivity analysis of this result on two crucial parameters: the rate of pure time preference, and the rate of risk aversion. We show that the social cost of carbon lies anywhere in between 0 and $120,000/tC. However, if we restrict these two parameters to match observed behavior, an expected social cost of carbon of $60/tC results. If we correct this estimate for income differences across the world, the social cost of carbon rises to over $200/tC.

Corresponding Author: Richard.Tol@esri.ie

[a] Economic and Social Research Institute, Dublin, Ireland
[b] International Max Planck Research School of Earth System Modelling, Hamburg, Germany
[c] Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
[d] Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands
[e] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA
[f] Department of Economics, Wesleyan University, Middletown, CT, USA

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The social cost of carbon (the SCC) estimates the discounted value of the damage associated with climate change impacts that would be avoided by reducing carbon emissions by one tonne. It is a useful measure for assessing the benefits of climate policy at any point in time. It is generally thought to increase over time, and textbook economics would recommend that carbon emissions be taxed by a price set equal to the SCC. The *Stern Review*[18-20] reported a SCC in excess of $300/tC in the absence of any climate policy – an estimate that lies well above the upper bound of $50/tC that was found in an extensive literature survey and meta-analysis[26]. Many analysts have attributed this high estimate to the very low rate of pure time preference adopted by the *Stern* author team[1,11,13,14,30].

Others[5,29] have argued that the *Stern Review* also included unusual assumptions about risk aversion. We respond to this observation by exploring the relative sensitivity of the SCC to both the pure rate of time preference *and* the rate of risk aversion. Our results support the hypothesis that the assumed rate of risk aversion is at least as important as the assumed rate of time preference in determining the social cost of carbon even though our analysis reveals an enormous range of estimates. Some are negative (that is, showing social benefits), but our positive estimates span *six* orders of magnitude on the positive side depending on both the pure rate of time preference and a standard measure of risk aversion.

Philosophers would likely confront this range by choosing a particular estimate based on what they deemed to be appropriate reflections of both parameters[3,4,12,15]. This approach was adopted in the *Stern Review*, but here we take a different tact. Instead of imposing our own normative values on the selection of a single SCC estimate, we look at the behaviours of democratically elected governments to infer distributions of the rates of risk aversion and pure time preference that are actually used in practice. We use the resulting probability density to constrain the estimates of the SCC and compute its expected value. Perhaps surprisingly, the *expected* social cost of carbon turns out to be reasonably close to the value reported in the *Stern Review*.

To be sure, climate change is a long-term problem. This is why the pure rate of time preference is so important. Greenhouse gas emission reduction over the near-term would mitigate future damages, but they would do little to alter the present climate and/or the present rate of change in climate impacts. The costs of emission abatement must therefore be justified by the benefits of avoided

impacts in the future. It follows that any statement about the desirability of climate policy necessarily contains a value judgement about the importance of future gains relative to present sacrifices. The discount rate employed in benefit and cost calculations over time can be thought of as the opportunity cost of investment, but it can also be seen as the relative value of consumption over time. The two are equivalent if the economy is in a dynamic equilibrium; and this equivalence means that time preference is not alone in playing a critical role in determining any SCC estimate.

To explain why, we note that people discount future consumption for two reasons. Firstly, they expect to become richer in the future, and so they care less about an additional dollar then than they do about an additional dollar today. Secondly, they are impatient. We also recall the so-called Ramsey discount rate r that was designed to sustain optimal saving over time[16]. It consists of three components:

(1) $\qquad r = \rho + \eta g$

where ρ is the rate of pure time preference, g is the growth rate of per capita consumption, and η is the elasticity of marginal utility of consumption.

Both motives of personal discounting can be detected in the Ramsey rule for dynamic optimality by considering the rate at which people would be willing to sacrifice a dollar of current consumption for additional consumption in the future (see the SOM for brief details). The pure rate of time preference is defined implicitly by the marginal rate of substitution between present and future consumption *under the condition that consumption levels in both periods are equal (so that g = 0).* In words, the definition of the pure rate of time preference calibrates inter-temporal trading so that individuals who anticipate constant levels of consumption from one period to the next would be willing to sacrifice one dollar of present consumption if he or she would be compensated with *$(1 + ρ)* of *extra consumption* in the next period. Higher values of ρ therefore reflect higher degrees of impatience because higher compensation would be required to compensate exactly for the loss of $1 in current consumption.

Consumption levels need not be constant over time, and the second term in Eq (1) works the implication of this fact into this trading calculus. While g measures the growth rate of material consumption, ηg reflects the growth rate of happiness measured in terms of underlying personal utility. If consumption were to climb by $g \cdot 100\%$ from one period to the next, then each future dollar would be worth $g \cdot \eta \cdot 100\%$ less (assuming no impatience so $\rho \equiv 0$). It follows that our individual would

consider sacrificing one dollar in current consumption only if he or she could be compensated by an amount equal to $(1 + g\eta)$ in the future.

In contemplating welfare-based equivalence of consumption over time, it is now clear that this trading-based accommodation of growing consumption works in exactly the same way as the pure rate of time preference in defining the rate at which the future needs to be discounted. Put another way, if one considered empirical estimates for both ρ and η that range from zero to three, then both parameters should play equally important roles in determining the appropriate discount rate. Perhaps because "impatience" is intuitively clear while the role of the "elasticity of marginal utility with respect to consumption" is not, the debate over how the SCC could be so high has focused undue attention over ρ almost to the exclusion of η.

This need not be the case; indeed, the utility-based association with the Ramsey discounting rule shows that this should not be the case. Climate change is not only a long-term problem; it is also a very uncertain problem and a problem that differentially affects people with widely different incomes. The rate of pure time preference ρ speaks only to the first characteristic of the climate policy problem – the time scale issue. The elasticity of marginal utility with respect to consumption, the parameter η, speaks to all three characteristics. It is, first of all, a measure of the curvature of the utility function, which maps material consumption to happiness. It indicates precisely the degree to which an additional dollar brings less joy as income increase. Moreover, the parameter η can also be interpreted as a measure of how one evaluates a gain of a dollar for rich person relative to a gain of a dollar for a poor person. This is why η is occasionally referred to as the parameter of inequity aversion. At the same time, curvature in the utility function can be viewed as a reflection of risk aversion. In this role, η explains why risk-averse people buy insurance; they are willing to pay a premium that is proportional in first order approximation to the parameter η to eliminate variability in outcomes because doing so increases their expected utility.[1]

Armed with these insights from the first principles of microeconomic theory, we used the integrated assessment model *FUND* to test the hypothesis that η could actually turn out to be more

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[1] The risk premium is, by definition, the difference between the expected outcome of a risky situation and the "certainty equivalent" outcome – the guaranteed outcome that would sustain a level of utility equal to expected utility across the full range of possible outcomes. For a risk averse individual, the certainty equivalent is always less than the mean because losses relative to the mean reduce utility more than equal gains above the mean.

important in determining the SCC than ρ. In many ways, *FUND* is a standard integrated assessment model[9,21,22,27]. It has simple representations of the demography, economy, energy, emissions, and emission reduction policies for 16 regions. It has simple representations of the cycles of greenhouse gases, radiative forcing, climate, and sea level rise. In other ways, though, *FUND* is unique. It is alone in the detail of its representation of the impacts of climate change. Impacts on agriculture, forestry, water use, energy use, the coastal zone, hurricanes, ecosystems, and health are all modelled separately – both in "physical" units and their monetary value[23,24]. Moreover, *FUND* allows vulnerability to climate change impacts to be an explicit function of the level and rate of regional development[25,28]. See the SOM for more details on the model.

We estimated the SCC cost of carbon by computing the total, monetised impact of climate change along a business as usual path and along a path with slightly higher emissions between 2005 and 2014. Differences in impacts were calculated, discounted back to the current year, and normalised by the difference in emissions. The SCC is thereby expressed in dollars per tonne of carbon at a point in time – the standard measure of how much future damage would be avoided if today's emissions were reduced by one tonne. More details on *FUND* are provided in the SOM.[2]

We estimated the SCC for a range of values for ρ and η, but we report our results in stages to highlight the triple role of η. We first consider results for cases in which η affected only the discount rate. That is, we pretended that uncertainty about climate change had been resolved and that income differences between countries were irrelevant. The second set of results put uncertainty back into the problem; the reported expected values of the SCC are the product of a Monte Carlo analysis of all the uncertain parameters in the *FUND* model. A third batch of results were drawn from the original world of perfect climate certainty, but social cost estimates applied equity weighting to climate-driven globally distributed differences in income. Finally, we report expected social cost estimates for cases in which both uncertainty and equity-weighing play a role – the cases where η plays its theoretically appropriate triple role.

Figure 1 shows the SCC cost of carbon for the four cases, varying both ρ and η while Figure 2 portrays various cross-sections. If we ignore concerns about equity and uncertainty (Panel A), the SCC roughly decreases with the discount rate. For $\rho = \eta = 0$, SCC = \$1,939/tC; it falls to SCC =

$10/tC for $\rho = \eta = 1$ and to SCC = -$5/tC for $\rho = \eta = 2$. The sign changes because climate change is initially beneficial to the world economy. For $\rho = \eta = 3$, however, SCC climbs back to -$4/tC because the discount rate is so high that it even discounts initial benefits significantly.

The profiles change when uncertainty is taken into account. Panel B shows that a maximum is still observed where $\rho = \eta = 0$ and the expected social cost of carbon, denoted E(SCC) equals $2,036/tC. This is a local maximum, though. E(SCC) falls monotonically as ρ increases. E(SCC) also falls initially as η (and thus the discount rate) increases, but it starts rising as a greater η values puts more emphasis on the tail of the distribution. For $\rho = 0$ and $\eta = 3$, E(SCC) = $152,155/tC. E(SCC) is negative only for $\rho \geq 2.7\%$ and $1.10 \leq \eta \leq 2.25$.

Panel C shows that the results are different again with equity weighing[2,8] and no uncertainty. For $\rho = \eta = 0$, SCC = $1,939/tC; since $\eta = 0$ implies equal weights, this is the global maximum. A local maximum appears at SCC = $122/tC when $\rho = 0$ and $\eta = 3$. Since this maximum is smaller than the expected social cost reported above for the second set of values for $\rho = 0$, $\eta = 3$, we see that uncertainty is a bigger concern for climate policy than equity, at least in terms of an aggregate measure like the SCC. A global minimum is observed when $\rho = \eta = 3$ and SCC = -$50/tC. It emerges because CO_2 fertilization brings short-term benefits even to poor countries that will be hurt by climate change in the longer term. For these parameters, long-term losses are heavily discounted and short-term benefits in developing countries are emphasized. See the Supplementary Online Material for the case without CO_2 fertilization.

Estimates of expected social cost are similar when equity weighting is added to the complication of uncertainty. Panel D reflects is a local a maximum at $\rho = \eta = 0$ as before where E(SCC) = $2,036/tC, but the global maximum is E(SCC) = $120,977/tC at $\rho = 0$, $\eta = 3$. E(SCC) is lowest for a high ρ and a medium η; E(SCC) = $9/tC, for example, at $\rho = 3.0\%$, $\eta = 0.90$. Note that the E(SCC) is strictly positive for this, the theoretically correct scenario.

For reference, Lord Stern of Brentford chose $\rho = 0.1\%$, $\eta = 1$; in our calibration through *FUND,* the result was E(SCC) = $721/tC. Since the *Stern Review* essentially ignored equity weighing, though, E(SCC) = $333/tC is a more comparable statistic. The *Stern Review* estimate E(SCC) = $314/tC, which is remarkable close. However, note that the *Review* used the PAGE[10] model – which

truncates the tails of distributions of input parameters, that *FUND* fully recognizes[3], but keeps vulnerability to climate change as in 1995 while *FUND* has vulnerability declining with development – the two main differences between the two models roughly offset one another.

We used two different approaches to inform our representations of combinations ρ and η that reflect actual practice across decision-makers. In the first, we worked with results from Evans and Sezer[6,7], who estimated $\eta = 1.49 \pm 0.19$ for 22 rich and democratic countries from income redistribution data[17]. They also independently estimated $\rho = 1.08 \pm 0.20$ using data on mortality rates. Assuming normality, these results support the probability density function on ρ and η displayed in Panel A of Figure 3. The first row of Table 1 records estimates of the expected value of the SCC derived from this distribution for the four cases described above (see Supplementary Online Material for details). Ignoring concerns about equity and uncertainty, E(SCC) = -\$1/tC. Considering either equity or uncertainty alone increases the estimate to 13/tC or 62/tC, respectively. Uncertainty is again seen to play a larger role in determining the social cost of carbon than equity. Considering both equity and uncertainty produces the fourth estimate: E(SCC) = \$210/tC. Equity and uncertainty reinforce one another.

Our second approach relied data on per capita consumption growth rates, inflation rates, and nominal interest rates for 27 OECD countries from 1970 to 2006. We interpreted observations of the real interest rate (r in equation (1) and the difference between the nominal rate and the rate of inflation) and the growth rate *g* as drawings from a bi-variate normal distribution. The Ramsey equation implies that realisations for *r* and *g* together support a linear combination for ρ and η. As a result, the bi-variate distribution for *r* and *g* implies a degenerate bi-variate distribution for ρ and η. Panel B of Figure 3 displays this distribution. The mean for η is 1.18, with a standard deviation of 0.80, but the distribution is right skewed with a mode of $\eta = 0.55$. The mean of ρ is 1.4%, with a standard deviation of 0.9%; the distribution is again right-skewed, this time with a mode of $\rho = 0.9\%$. The characteristics of this distribution are not inconsistent with the underlying distributions reported by Evans and Sezer, but it does clearly differ in shape. The second row of Table 1 shows the sensitivity of E(SCC) estimates to the difference. Ignoring uncertainty and equity, E(SCC) = \$41/tC; it is much higher than the estimate reported in the first row from the Evans and Sezer distribution because lower values of ρ

[3] Note that we trim the top and bottom .1% of results.

and η are deemed more likely. As before, considering either equity or uncertainty increases the E(SCC), this time to \$59/tC and \$117/tC, respectively. The effects of equity and uncertainty are now less pronounced because extreme values of ρ and η receive lower probability mass than before. Finally, as before, uncertainty dominates equity. However, in this case, equity moderates uncertainty; considering both simultaneously produces an estimate for E(SCC) of \$228/tC. Again, equity and uncertainty reinforce one another.

The third row of Table 1 shows E(SCC) estimates for a combined probability density function of ρ and η produced by multiplying the two PDFs in Figure 3 and rescaling them to integrate to unity. The estimates lie in between the previous results, but closer to the initial results derived from the Evans and Sezer PDF. The qualitative pattern is the same, though. Uncertainty dominates, and is reinforced by equity. Combining all of this information, our final estimate is E(SCC) = \$206/tC.

Lord Stern[18] has expressed a preference for debating philosophically about the appropriate discount rate for the benefits of mitigation. We bow out of that debate by exploring the ramifications of actual decision makers and actual developed economies. We find that aversion to risk aversion is as important in determining SCC estimates as time preference. More specifically, we offer high estimates for the SCC given operational combinations of risk aversion and time preference even with a model that incorporates relative conservative damage estimates (including benefits early) and autonomous adaptation drive by regional economic development.
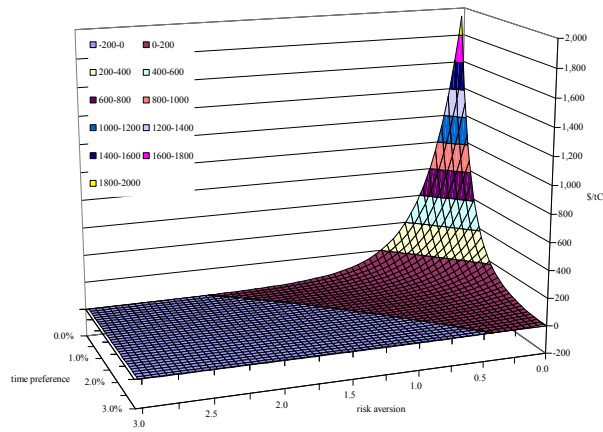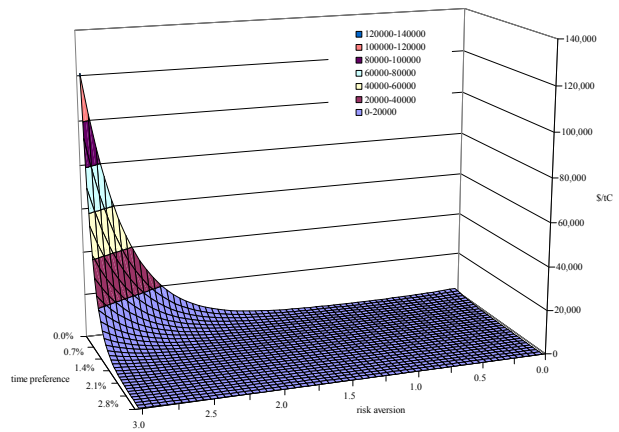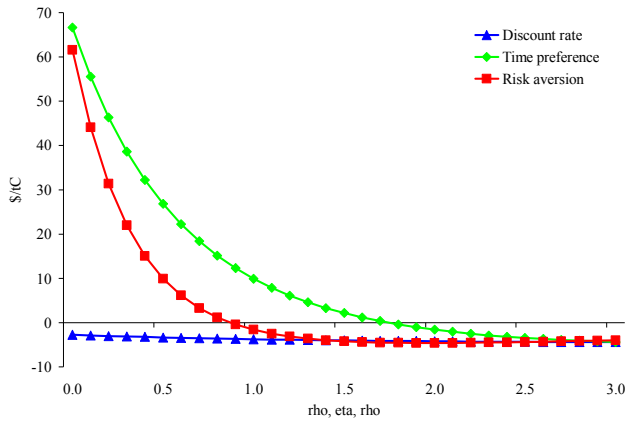
Panel A
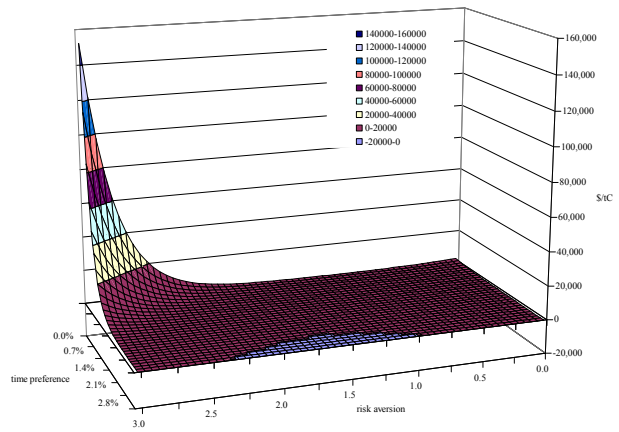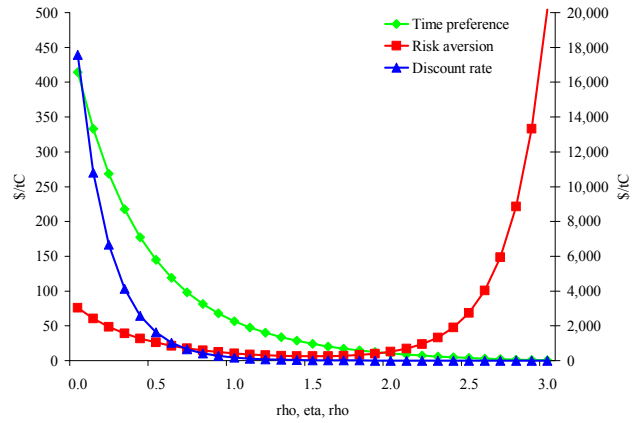

Panel B
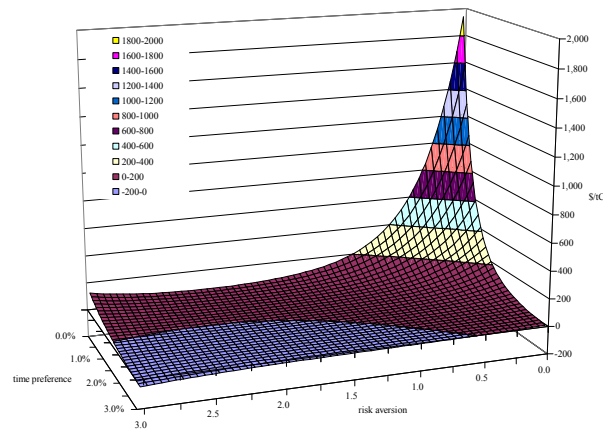
Panel C

Panel D

Figure 1. The marginal damage cost of carbon emissions as a function of the rate of time preference and the rate of risk aversion.

Panel A (top left) shows the sensitivity of SCC estimates without equity weighting and without uncertainty; low pure rates of time preference and risk aversion produce high SCC estimates because they work exclusively through the discount rate. Panel B (top right) shows the sensitivity of SCC estimates to uncertainty without equity weighting; low rates of time preference produce higher estimates, but uncertainty dominates especially for high levels of risk aversion where the associated

risk premium climbs enormously. Panel C (bottom left) shows the sensitivity of SCC estimates to equity weighting derived from the "inequity aversion) interpretation of η and without uncertainty; higher aversions to inequity reduce the SCC for any time preference because the positive gains in developing countries from CO_2 fertilization dominate "downstream" losses that are, by virtue of the higher values for η, discounted more severely. Panel D (bottom right) shows the sensitivity of SCC estimates to equity weighting with uncertainty fully represented; the moderating effect of higher values for η is dominated by the effect of uncertainty.
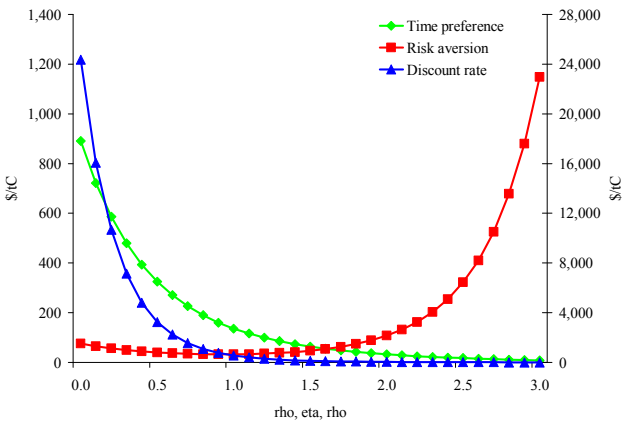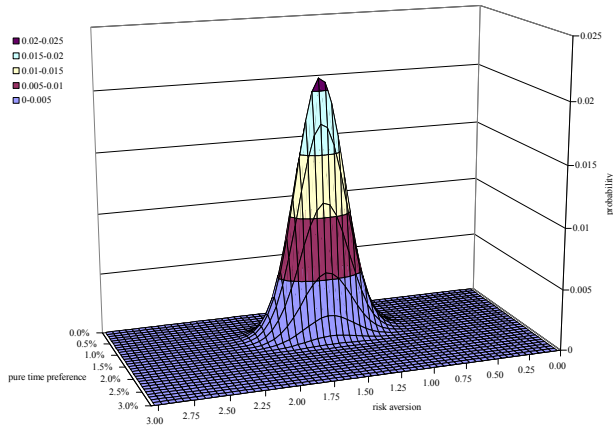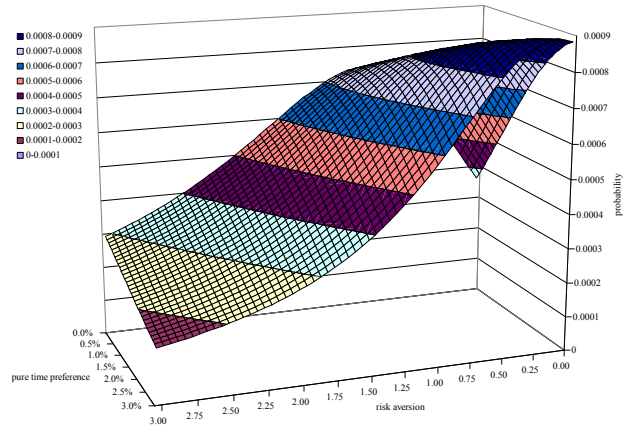
Panel A

Panel B
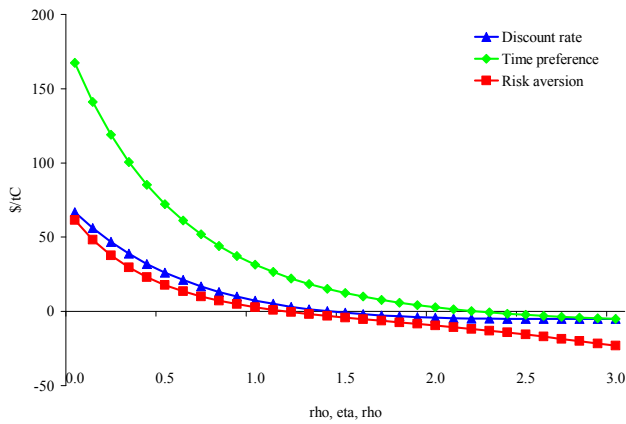
Panel C

Panel D

Figure 2. The SCC as a function of the rate of time preference (green diamonds for a rate of risk aversion of 1.0)**, the rate of risk aversion** (red squares for a rate of time preference of 2.0), and of **the rate to time preference** (blue triangles for a rate of risk aversion adjusted to maintain the discount rate at 5.0 assuming that consumption grows at 2.0% per year – right axis)**.**

Panel A (top left) shows contours without equity weighting and without uncertainty. Negative values for SCC are possible for high rates of risk aversion and/or time preference (and guaranteed for a 5% discount rate); this is an indication of the conservative damage estimates embodied in *FUND*. Panel B (top right) displays contours with η working as a risk aversion parameter given complete manifestation

of uncertainty but ignoring its role as equity weighting parameter at any point in time; the U-shaped contour associated with risk aversion is particularly instructive – the discounting effect of high values is dominated by the risk-premium effect of increased aversion to risk. Panel C (bottom left) shows contours with η working to produce equity weights without uncertainty; the early agricultural benefits of CO_2 fertilization in developing countries produces negative estimates for SCC for high discount rates born of high rates of risk aversion and/or time preference. Panel D (bottom right) allows η to work both as a source of equity weighting and as a measure of risk aversion given climate and socio-economic uncertainty; the U-shaped contours of the uncertainty only case from Panel B return.

Panel A

Panel B

Figure 3. Probability density functions of risk aversion and time preference

Panel A displays the distribution reported by Evans and Sezer. Panel B was derived from the Ramsey rule using OECD data.

Table 1. Estimates of the Expected Social Cost of Carbon ($/tC).

	No	No	Yes	Yes
Uncertainty Included?	No	No	Yes	Yes
Equity weighting Included?	No	Yes	Yes	No
Rate of pure time preference and rate of risk aversion from Evans and Sezer	-0.7	12.6	210.1	61.6
Inference from interest rate and consumption growth rates from OECD countries	40.6	58.7	227.8	117.4
Both	-0.4	13.2	205.5	60.7

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APPENDICES

A. A utility-based rationale for Equation (1)

To uncover the utility-based interpretation of the Ramsey (1928) optimal saving rule, consider a two period environment wherein inter-temporal discounted utility is given by

$$(S1) \quad U(C_1, C_2) = U(C_1) + \frac{U(C_2)}{1+\rho}$$

with C_t indicating consumption in period t ($t = 1,2$). Totally differentiating this relationship defines an inter-temporal marginal rate substitution (i.e., the rate at which an individual would trade current consumption for future consumption while maintaining the same level of discounted utility):

$$(S2) \quad \left.\frac{\partial C_2}{\partial C_1}\right|_{U=U^*} = \frac{U'(C_1)}{U'(C_2)/1+\rho} \approx \frac{U'(C_1)(1+\rho)}{U'(C_1)(1-\eta g)} = \frac{(1+\rho)}{(1-\eta g)} \approx 1 + \rho + \eta g$$

The interpretation in the text – that the Ramsey rule can be interpreted as representing the sum of an impatience effect and the effect of diminishing marginal utility with increasing consumption – follows.

B.   FUND details including website address.

This paper uses version 3.0 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 3.0 of *FUND* corresponds to version 1.6[15,18,20], except for the impact module.[10,16,17] TA full list of papers, the source code and the technical documentation for the model can be found on line at http://www.fundmodel.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. The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2200.

The period of 1950-2000 is used for the calibration of the model, which is based on the *IMAGE* 100-year database[1]. The scenario for the period 2010-2100 is based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f[9]. The 2000-2010 period is interpolated from the immediate past (http://earthtrends.wri.org), and the period 2100-2300 extrapolated.

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

The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and 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 impacts are dead-weight losses to the economy[6]. 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, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model[7,11]. The model also contains sulphur emissions[19].

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is as in the IPCC[13]. 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 follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs[12]. 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[8].

The climate impact module[16,17] includes the following categories: agriculture, forestry, 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 can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation[17].

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all 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 literature2. The value of emigration is set to be 3 times the per capita income14, the value of immigration is 40 per cent of the per capita income in the host region2. 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 19905. 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 19905. The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units[16]. Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative[17].

The impacts of climate change on coastal zones, forestry, 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[17].

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) [17]. The income elasticities [17] are estimated from cross-sectional data.

The social cost of carbon (*SCC*) is estimated by running the model twice, perturbed and unperturbed. In the perturbed run, an additional one million metric tonnes of carbon are emitted in each year between 2001 and 2010. The difference in impacts is computed and discounted back to the year 2000, using the discount rate as specified in Equation (S2). The difference is then divided by 10 mln tC to obtain an incremental cost estimate. That is,

$$(S3) \quad SCC_r = \sum_{t=2001}^{2300} \frac{I_{t,r}\left(\sum_{s=1950}^{t-1} E_s + \delta_s\right) - I_{t,r}\left(\sum_{s=1950}^{t-1} E_s\right)}{\prod_{s=2001}^{t} 1 + \rho + \eta g_{s,r}} \Bigg/ \sum_{t=2001}^{2010} \delta_t$$

where

- *SCC_r* is the regional social cost of carbon (in US dollar per tonne of carbon);
- *r* denotes region;
- *t* and *s* denote time (in years);
- *I* are monetised impacts (in US dollar per year);
- *E* are emissions (in metric tonnes of carbon);
- *δ* are additional emissions (in metric tonnes of carbon);
- *ρ* is the pure rate of time preference (in fraction per year);
- *η* is the elasticity of marginal utility with respect to consumption; and
- *g* is the growth rate of per capita consumption (in fraction per year).

We first compute the *SCC* per region, and then aggregate, as follows

$$(S4) \quad SCC = \sum_{r=1}^{16} \left(\frac{Y_{2000,world}}{Y_{2000,r}}\right)^{\varepsilon} SCC_r$$

where

- SCC is the global social cost of carbon (in US dollar per tonne of carbon);

- SCC_r is the regional social cost of carbon (in US dollar per tonne of carbon);
- r denotes region;
- Y_{world} is the global average per capita consumption (in US dollar per person per year);
- Y_r is the regional average per capita consumption (in US dollar per person per year); and
- ε is the rate of inequity aversion; $\varepsilon=0$ in the case without equity weighing; $\varepsilon=\eta$ in the case with equity weighing.

In the case of uncertainty, we compute the expected value of the *SCC*, as follows:

$$(S5) \quad \mathrm{E}(SCC) = \frac{1}{MC} \sum_{i=1}^{MC} SCC(\theta_i)$$

where

- $\mathrm{E}(SCC)$ is the expected value of the social cost of carbon (in US dollar per tonne of carbon);
- i indexes the Monte Carlo run;
- MC is the number of Monte Carlo runs; $MC = 1000$; and
- θ is the vector of uncertain input parameters, fully specified on http://www.fundmodel.org/

C. The rate of risk aversion, the pure rate of time preference, and the discount rate

We compute the *SCC* and the E(*SCC*) for a range of the pure rate of time preference (ρ) and the rate of risk aversion (η), and we also compute a weighted average using three alternative bivariate PDFs for ρ and η, as follows:

$$(S6) \quad SCC* = \int\limits_{H}\int\limits_{P} SCC(\rho,\eta) f(\rho,\eta) \mathrm{d}\rho \mathrm{d}\eta$$

The first bi-variate PDF of ρ and η assumes that these parameters are normally distributed with μ_ρ=1.08%, μ_η=1.49, σ_ρ=0.20%, σ_η=0.19 and $\sigma_{\rho\eta}$=0. See Table S1. The second bi-variate PDF is degenerate. It corresponds to a bi-variate normal PDF of r and g with μ_r=3.45%, μ_g=2.70, σ_r=2.56%, σ_g=1.61 and σ_{rg}=0 (see Table S2) and $r = \rho + \eta g$. The third bi-variate PDF is the convolution of the first two.

Table S1. Data on the rates of pure time preference and risk aversion.

	ρ	g	η^a	η^b
Australia*	1.5	1.9	1.4	1.7
Austria	1.0	2.7	1.6	1.6
Belgium	1.0	2.3	1.5	1.6
Czech Rep	1.1	1.4	1.4	1.4
Denmark	1.1	1.0	1.2	1.3
Finland	1.0	2.2	1.6	1.6
France	0.9	1.8	1.3	1.3
Germany	1.0	2.2	1.6	1.5
Greece	1.0	2.5	1.7	1.5
Hungary	1.3	1.6	1.2	1.4
Ireland	0.8	3.0	1.6	2.0
Italy	1.0	2.5	1.5	1.4
Japan*	1.5	2.5	1.4	1.4
Luxembourg	0.9	2.5	1.8	1.8
The Netherlands	0.9	1.8	1.5	1.6
Poland	1.0	4.6	1.1	1.1
Portugal	1.0	2.7	1.6	1.7
Slovakia	1.1	3.7	1.6	1.5
Spain	1.0	2.3	1.6	1.6
Sweden	1.1	1.2	1.1	1.4
UK	1.0	2.0	1.5	1.5
USA*	1.5	2.2	1.3	1.4
Mean	1.08	2.30	1.46	1.51
St dev	0.20	0.79	0.19	0.19

[a] Risk aversion evaluated at the average wage.
[b] Average risk aversion evaluated at a range of wages.
Sources: [4] and [3]*.

Table S2. Data on the growth rate of per capita income and the real rate of interest.

	Per capita growth[a]		Real interest[b]		Corr	N	Year	
	mean	St dev	Mean	St dev			first	last
Australia	2.42	0.88	3.25	3.63	0.28	30	1971	2005
Austria	1.99	0.99	3.54	1.22	0.19	16	1990	2006
Belgium	2.44	1.47	3.85	2.42	-0.29	33	1970	2005
Canada	2.48	1.41	3.56	2.58	0.08	32	1970	2005
Czech Rep	4.45	1.68	2.45	1.06	-0.08	5	2001	2005
Denmark	1.90	1.30	4.16	1.91	0.09	18	1988	2006
Finland	3.58	1.33	4.60	1.96	0.32	14	1988	2005
France	2.17	1.37	3.58	2.10	-0.21	34	1970	2005
Germany	2.46	1.28	3.86	1.25	-0.01	32	1970	2006
Greece	3.86	0.51	1.86	1.32	-0.20	9	1998	2006
Iceland	4.03	1.57	5.65	1.60	0.09	9	1995	2005
Ireland	4.80	2.68	3.25	3.40	0.21	28	1976	2005
Italy	1.57	0.98	3.90	2.03	0.31	12	1993	2006
Japan	1.98	1.25	2.60	0.87	0.03	13	1989	2005
Korea	4.39	1.36	2.30	1.11	-0.24	5	2001	2005
Luxembourg	3.69	2.23	2.83	1.78	0.03	11	1995	2005
Netherlands	2.46	1.09	3.51	2.20	-0.23	32	1970	2006
New Zealand	2.46	1.59	2.67	3.88	-0.20	26	1970	2005
Norway	2.39	1.33	4.86	1.65	0.20	20	1985	2005
Poland	4.17	1.84	4.47	1.11	-0.51	5	2001	2005
Portugal	2.35	1.65	3.07	2.12	0.73	11	1994	2005
Slovak Rep	5.55	1.67	-0.15	2.94	-0.23	5	2001	2005
Spain	2.63	1.33	3.84	2.46	0.32	25	1981	2006
Sweden	2.61	1.25	5.00	1.79	-0.10	16	1987	2005
Switzerland	1.87	1.13	1.50	1.66	-0.04	27	1970	2005
UK	2.82	1.20	3.22	3.72	-0.02	30	1970	2005
USA	2.76	1.27	3.28	2.39	0.18	30	1970	2005
Total	2.70	1.61	3.45	2.56	0.01	528	1970	2006

[a] Gross domestic product (expenditure approach) per capita in constant prices.
[b] Long-term interest rate minus the percentage change in the consumer price index (all items).
Source: OECD.Stat Monthly Economic Indicators (http://stats.oecd.org)

D. The impact of CO_2 fertilization on the social cost of carbon.

In the main text, we find that social cost of carbon is positive for a high value of η if equity weighing is included and uncertainty is not. We assert that this is because of CO_2 fertilization of agriculture, which has large benefits in developing countries in the short term. High values of eta emphasize these benefits. In order to test this assertion, we reran the model with the CO2 fertilization switched of. Figure S1 compares the results. With CO_2 fertilization, the SCC falls with rising η. Without CO2 fertilization, the SCC first falls (as the discount rate increases) but then starts rising (as the rising discount rate is more than compensated by the increasing equity weights).

Panel A   Panel B
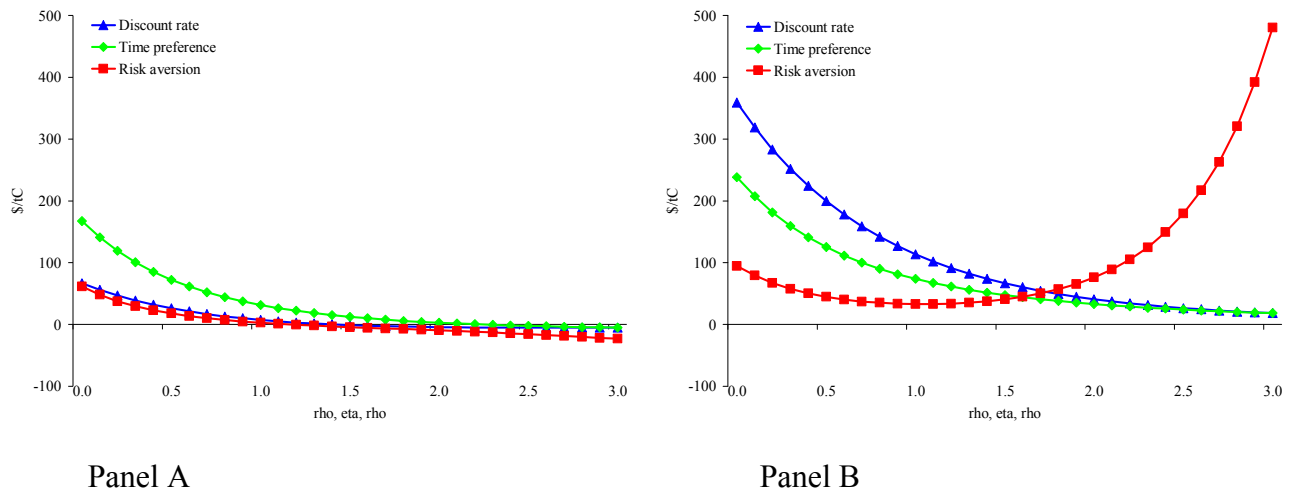
Figure S1. The SCC as a function of the rate of time preference (green diamonds for a rate of risk aversion of 1.0)**, the rate of risk aversion** (red squares for a rate of time preference of 2.0), and of **the rate to time preference** (blue triangles for a rate of risk aversion adjusted to maintain the discount rate at 5.0 assuming that consumption grows at 2.0% per year)**.**

Both panels show contours with equity weights but without uncertainty. Panel A includes the immediate, positive effects of CO2 fertilization on agriculture across the world, whereas Panel B assumes no CO2 fertilization. Panel A equals Figure 2, Panel C (rescaled).

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