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The Time Evolution of the Social Cost of Carbon: An Application of Fund

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Abstract The authors estimate the growth rate of the social cost of carbon. This is an indication of the optimal rate of acceleration of greenhouse gas emission reduction policy over time. The authors find that the social cost of carbon increases by 1.3% to 3.9% per year, with a central estimate of 2.2%. Previous studies found an average rate of 2.3% and a range of 0.9 to 4.1%. The rate of increase of the social carbon depends on a range of factors, including the pure rate of time preference, the rate of risk aversion, equity weighting, the socioeconomic and emission scenarios, the climate sensitivity, dynamic vulnerability, and the curvature of the impact functions.

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1. Introduction

Investors in new technologies or long-lived capital to reduce greenhouse gas emissions require a reasonable degree of certainty about the intensity of future climate policy. A carbon tax that rises at a pre-announced rate (periodically reviewed) is one option to provide such predictability. If there is some agreed long-term target that implies a fixed budget of allowed emissions, then the price of carbon should rise at the rate of discount. If, on the other hand, abatement targets are set by cost-benefit analysis, then the carbon price should equal the marginal damage costs and rise over time at the same rate as the marginal damage costs rise. The literature contains only a few explicit discussions of the evolution of the social cost of carbon over time. This paper presents new numbers and explores their sensitivity to key assumptions.

There are over 300 estimates of the social cost of carbon (Tol 2009), but only a minority of studies present estimates for marginal impacts at different points in time (Clarkson and Deyes 2002;Cline 1993;Fankhauser 1995;Haraden 1992;Haraden 1993;Hope 2008;Maddison 1995;Nordhaus 1993;Nordhaus 1994;Nordhaus 2008;Nordhaus and Boyer 2000;Nordhaus and Popp 1997;Nordhaus and Yang 1996;Peck and Teisberg 1993;Roughgarden and Schneider 1999;Sohngen 2009;Tol 1999;Wahba and Hope 2006). Evidence about the shape or growth rate of the marginal damages from the existing literature is somewhat contradictory. One study (Hope 2008) explicitly states that the social costs of carbon rise exponentially over time, while another (Clarkson and Deyes 2002) states that the increase is linear. The remaining studies present a time profile without commenting on its shape, but the majority of studies show an accelerating increase over time. Computing the annual growth rates, we find that the average of the 22 estimates is an increase of 2.3% per year,[1] with a standard deviation of 0.9%.[2] The highest estimate (4.1%) is due to (Haraden 1992) and the lowest estimate (0.9%) to (Roughgarden and Schneider 1999).[3] These papers all present the time evolution of the social cost of carbon without much comment on the underlying drivers of the change in SCC over time. The current paper explicitly discusses the time evolution of SCC and how specific parameters impact the way it is expected to change over time.

The paper is organized as follows: Section 2 presents the model, Section 3 discusses the results for the base case and a number of sensitivity analyses, and Section 4 concludes.

2. The model

This paper uses version 3.5 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 3.5 of *FUND* corresponds to version 1.6 (Tol et al. 1999;Tol 2001;Tol 2002c) except for the impact module described in (Link and Tol 2004;Narita et al. 2009;Narita et al. 2010;Tol 2002a;Tol 2002b). A full list of papers, the

[1] (Yohe et al. 2007) state that "current knowledge suggests a 2.4% per year rate of growth".

[2] The average absolute increase is $1.18/tC per year, with a standard deviation of $1.48/tC.

[3] (Yohe et al. 2007) state that "current knowledge suggests a 2.4% per year rate of growth". Yohe et al. (2007) also reports a range of 2% to 4% per year. These estimates come from a single model and study.

source code, and the technical documentation for the model can be found on line at http://www.fund-model.org/.

The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States.

The model runs from 1950 to 3000 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs.[4] The centuries after the 21st are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2300. The terminal period is 3000 to provide a proper time horizon for estimates with a low discount rate.

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 storms. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org). It is extrapolated based on the statistical relationship between urbanization and per capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

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 (Hammitt et al. 1992;Maier-Reimer and Hasselmann 1987). The model also contains sulphur emissions (Tol 2006).

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

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is as in the IPCC (Ramaswamy et al. 2001). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a best guess e-folding time of 66 years for a climate sensitivity of 3.0. In the base case, the global mean temperature rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents. Regional temperatures follow from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al. 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 500 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario (Kattenberg et al. 1996).

The climate impact module includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, energy consumption, water resources, unmanaged ecosystems (Tol 2002a;Tol 2002b), diarrhoea (Link and Tol 2004), and tropical and extra tropical storms (Narita et al. 2009;Narita et al. 2010). Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (Tol 2002b).

People can die prematurely due to climate change, or they can migrate because of sea level rise. Like all 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 (Cline 1992). The value of emigration is set to be 3 times the per capita income (Tol 1995), the value of immigration is 40 per cent of the per capita income in the host region (Cline 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (Fankhauser 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 (Fankhauser 1994). The wetland value is assumed to depend on per capita income, population density and wetland scarcity. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, storm damage, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (Tol 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the

speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (Tol 2002b).

The impacts of climate change on coastal zones, forestry, tropical and extratropical storm damage, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (Tol 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) are projected to become less vulnerable at least over the long term (Tol 2002b). The income elasticities (Tol 2002b) are estimated from cross-sectional data or taken from the literature.

Overall, the impact of climate change will change over time as a function of changing regional socioeconomic conditions—income, population, and technology; global greenhouse gas emissions and their accumulation in the atmosphere; regional temperature levels and rates of change; and changing regional vulnerability driven by changing socioeconomic conditions.

We estimated the social 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 in the ten years following the year for which we compute the social cost of carbon. Differences in impacts were calculated, discounted back to the current year, and normalised by the difference in emissions. Note that to be consistent with changing economic conditions over time, the discount rate is not constant over time or identical across regions, but instead a function of regional economic growth in per capita income. 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 emissions at that point in time were reduced by one tonne. That is,

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

$$\delta_s = \begin{cases} \varepsilon & \text{for } t \le s < (t+10) \\ 0 & \text{for all other cases} \end{cases}$$

where

- $SCC_{t,r}$ is the regional social cost of carbon for a marginal emission in the year t (in 1995 US dollar per tonne of carbon);
- r denotes region;
- t and s denote time (in years);
- D are monetised impacts (in US dollar per year);

- E are carbon dioxide emissions (in metric tonnes of *carbon*);
- δ are additional emissions (in metric tonnes of *carbon*);
- ρ is the pure rate of time preference (in percent per year);
- η is the elasticity of marginal utility with respect to consumption; and
- g is the growth rate of per capita consumption (in percent per year).

We first compute the $SCC_{t,r}$ per region, and then aggregate, as follows

$$SCC_t = \sum_r \left(\frac{c_{t,ref}}{c_{t,r}} \right)^{\varepsilon} SCC_{t,r} \qquad (2)$$

where

- SCC_t is the global social cost of a marginal carbon emission release in the year t (in US dollar per tonne of carbon);
- $SCC_{t,r}$ is the regional social cost of a marginal carbon emission release in the year t (in US dollar per tonne of carbon);
- r denotes region;
- $cc_{t,r}$ is the regional average per capita consumption at time t (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 order to examine how it changes over time, the SCC is calculated in 10 time periods: 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100 for each of the five scenarios and under multiple discounting assumptions. The terminal period is fixed for all runs, but far enough into the future to be inconsequential to the results.

3. Results and sensitivities

The sensitivity of the SCC estimates over time to a number of parameters is examined. Specifically, we consider the implications of discounting, equity weighting, socioeconomic and emissions scenarios, and the specification of the damage function to the SCC over time. Across sensitivity scenarios, we use a benchmark base case with pure rate of time preference of 1%, no equity weighting, FUND default socioeconomic assumptions, climate sensitivity of 3 degrees Celsius, and the FUND damage functions. The benchmark is for expository convenience and should not be construed as a best guess. It is simply one of many possible futures.

3.1. Discount rate and equity weighting

Figure 1 shows the social cost of carbon as a function of the time of emission for three alternative pure rates of time preference with the other assumptions fixed. For emissions in 2010, the estimate is \$186/tC for a 0.1% pure rate of time preference, \$30.3/tC for a

1% rate, and $1.33/tC for a 3% rate (all in 1995 US dollar).[5] For later emissions, the social cost of carbon is higher because the increment occurs on top of a higher level of warming and impacts net adaptation, which increases with the size of the climate signal and per capita income. There is a second reason, however. The absolute size of the (incremental) impact increases with the size of the economy. Later emissions therefore do more damage in absolute terms.

The annual average 2010-2100 growth rate of the social cost of carbon is 2.2% per year for 0.1% pure rate of time preference, 2.2% for a 1% rate, and 3.9% for a 3% rate. A high discount rate emphasizes the initial impacts of climate change, which are low because there are benefits of climate change in the short term (carbon dioxide fertilization, reduced heating demand, fewer cold-related deaths) which saturate in the medium term. The growth rates of the social cost of carbon compare to an assumed global rate of population growth of 0.5%, a global growth rate of per capita income of 1.4% and a global growth rate of the economy of 2.0%. For a rate of risk aversion of unity, the social cost of carbon therefore grows faster than the consumption discount rate for a pure rate of time preference of 0.1% and slower for a pure rate of time preference of 3.0%, while for a 1% rate the social cost of carbon roughly (but coincidentally) grows with the discount rate.

Figure 2 shows the social cost of carbon with and without equity weights, assuming a 1% pure rate of time preference. Without equity weights (as was the case in Figure 1), the social cost of carbon is $30.3/tC in 2010. This increases to $91.5/tC with average equity weights and to $563/tC for US equity weights, and falls to $8.83/tC for African equity weights. The social cost of carbon increases over time, but at different rates. Without equity weights, the social cost of carbon grows at 2.2% per year. With world average equity weights, the growth rate falls to 1.3%. This is because the emissions scenarios assume convergence of per capita incomes, so that equity weights become less pronounced over time. With US equity weights, the growth rate of the social cost of carbon is only 1.1% per year. With African equity weights, on the other hand, the social cost of carbon grows at 2.2% per year, indicating that Africa's economic growth is assumed to lag behind that of other developing countries.

3.2. Socioeconomic and emissions scenarios

Figure 3 shows the social cost of carbon, without equity weights (and with 1% pure rate of time preference), for five alternative socio-economic and emissions scenarios. The base scenario, FUND, has a social cost of carbon of $30.3/tC in 2010. SRES B2 is almost the same ($29.1/tC) while SRES A2 is much higher ($45.4/tC). SRES A1 ($12.1/tC) and B1 ($8.09/tC) are lower. The differences between the scenarios are driven, first, by the size of the economy and, second, by the amount of warming. These scenarios represent very different futures—globally and regionally. In particular, while the other scenarios represent world's consistent with today's trends, B1 is a scenario with global emissions below today's levels and a future path not likely attainable without immediate international mitigation action on climate change.

[5] $186, $30.3, and $1.33/tC = $51, $8.3, and $0.36/tCO$_2$

The growth rate of the social cost of carbon is lowest in the FUND scenario (2.21%), followed by SRES A2 (2.3%), B2 (2.3%), B1 (3.0%) and A1 (3.1%). Figure 4 compares the average annual growth rate of the social cost of carbon to the growth rate of population, income per capita, and gross domestic product. Figure 4 suggests that higher economic growth rates lead to a more rapid growth of the social cost of carbon – as climate change would be worse and impact a larger economy. This result suggests that emissions and climate increases associated with higher income outpace improvements in adaptive capacity. Thus, future energy technology assumptions are important, and lower carbon technologies with similar income growth could result in lower SCC growth.

3.3. Climate sensitivity

Figure 5 shows the social cost of carbon under the FUND scenario for three alternate climate sensitivities. In 2010 in the base scenario, equilibrium warming is 3.0ºC for a doubling to the atmospheric concentration of carbon dioxide and the social cost of carbon is $30.3/tC. Under climate sensitivities of 2.0ºC and 4.5ºC, the social cost of carbon falls to $11.5/tC and rises to$64.5/tC, respectively.

The climate sensitivity impacts the rate at which temperatures change for a given level of emissions and would therefore be expected to impact the growth rate of the social cost of carbon. On average within the FUND scenario, the SCC rises by 2.2% per year if the climate sensitivity is 3.0ºC. Interestingly, the growth *rate* increases for both a higher and a lower climate sensitivity, to 2.5% for climate sensitivities of 2.0ºC and 4.5ºC. This result may seem surprising at first glance. However, if the climate sensitivity is low, initial marginal impacts are very small so that growth is rapid. If the climate sensitivity is high, temperature change is rapid and marginal impacts quickly escalate. So while climate sensitivity seems to have a strictly positive impact on the SCC level estimates, the growth rate of the SCC appears to be somewhat U-shaped as a function of climate sensitivity.

3.4. Damage function specification

Figure 6 shows the social cost of carbon, for a climate sensitivity of 3.0ºC, for alternative specifications of the impact functions. In the benchmark base case, the social cost of carbon is $30.3/tC in 2010. This falls to $2.41/tC if all impact functions are linear in temperature. Although some impact functions are sublinear (e.g., reduction in heating demand), the superlinear impacts clearly dominate.

In the standard model base case, the vulnerability to climate change evolves as economies develop. Some impacts (e.g., infectious disease) fall with economic growth, other impacts (e.g., agriculture) rise more slowly than economic growth, and yet other impacts (e.g., biodiversity) rise faster than economic growth. FUND is the only integrated assessment model to include dynamic vulnerability. In order to mimic other models, we let all impacts be proportional to GDP. In that case, the social cost of carbon increases to $75.0/tC. We also consider the case in which impacts are a function of climate only. If SCC does not depend on income at all, then the social cost of carbon falls to $5.15/tC.

In the standard model, the social cost of carbon rises by 2.2% per year from 2010-2100. If impacts are a function of climate only, the social cost of carbon rises by 1.3% per year. If impacts are proportional to GDP, the social cost of carbon rises by 2.6% per year. This

confirms that, at least in FUND, vulnerability to climate change falls with development, and that this effect is substantial.

If impacts are linear in climate change, the social cost of carbon falls over time to -$18.8 for emissions in 2100. The social cost of carbon falls because incremental carbon dioxide has a diminishing effect on warming as concentrations rise, and because vulnerability to climate change falls with development. In the standard model, these two effects are more than offset by the superlinearity of the impacts, i.e., incremental damage is worse if damage is already high. In the linear model, this does not hold and the social costs of carbon fall.

Another feature of FUND is the positive effect that CO_2 has on crop growth, the carbon dioxide fertilization effect. Figure 6 shows the social cost of carbon for the standard model with and without carbon dioxide fertilization. With fertilization, the social cost of carbon in 2010 is $30.3/tC. Without fertilization, the social cost of carbon is $52.0/tC. Carbon dioxide fertilization has a sizeable, positive impact in the near term, and therefore on the net present value. With carbon dioxide fertilization, the social cost of carbon grows by 2.2% per year from 2010-2100. Without fertilization, the growth rate is 1.9%. This is because carbon dioxide fertilization saturates—at some point the crop productivity benefits of the additional CO_2 diminish and other factors lead to declining productivity (e.g. heat stress, and moisture availability).

4. Discussion and conclusion

In this paper, we present new estimates of the growth rate of the social cost of carbon, using the integrated assessment model FUND. Our best estimate of the growth rate of the social cost of carbon (2.2%) compares well with the average growth rate in the literature (2.3%). Figure 8 shows that 60% of previous estimates are smaller than our estimate, while 40% are larger. The range of growth rates of the social cost of carbon in this paper (1.3%-3.9%) is narrower than the range found in the literature (0.9%-4.1%), with the exception of the linear model for which the social cost of carbon falls over time. This suggests that FUND would match the maximum growth rate in the literature if the impact functions were made more non-linear.

We find that the social cost of carbon rises more slowly than the discount rate (unless one assumes a low pure rate of time preference and rate of risk aversion). That is, emission abatement is a normal good (Anthoff et al. 2009) – rather than a luxury good as is often assumed (Hoel and Sterner 2007;Sterner and Persson 2008). The reasons are that vulnerability to climate change falls as poor countries develop and that incremental carbon dioxide causes less warming as concentrations rise. Investments in emission reductions get more attractive as the growth rate of the carbon price increases.

Estimates of the total or marginal impact of climate change typically come with a long list of caveats (Kuik et al. 2008). However, the focus on the growth rate of the social cost of carbon and our estimate is similar to previous estimates. This suggests that our results are reasonably robust to variations in the model specifications – and this is indeed confirmed by our sensitivity analyses. There are a few aspects in particular that we did not consider. One would expect that the uncertainty about the impact of climate change

grows the further out in time we look (Weitzman 2009). This would imply that the certainty equivalent social cost of carbon increases faster than our base estimate of the social cost of carbon. Our estimate for riskier socioeconomic and climate conditions support this. The test of this hypothesis however is deferred to later research. Also important will be the evaluation of the social cost of non-CO_2 greenhouse gases over time, which have different atmospheric lifetimes and radiative forcing implications than carbon dioxide emissions.

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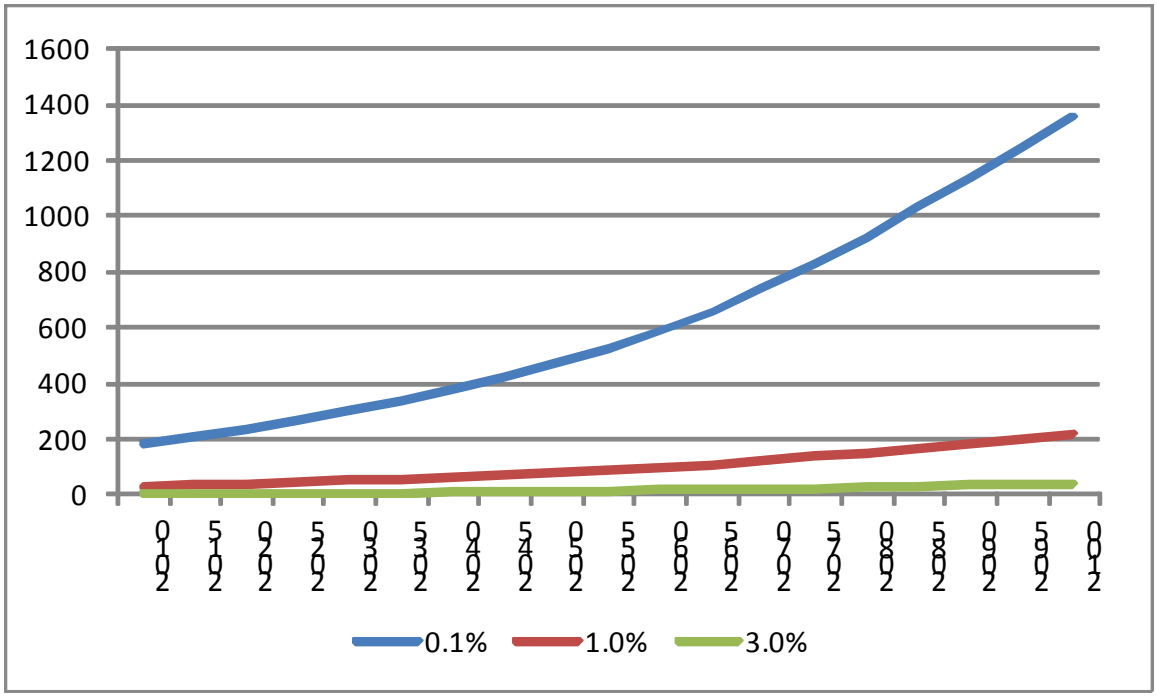

Figure 1. The social cost of carbon ($/tC) as a function of the time of emission for alternative rates of pure time preference.

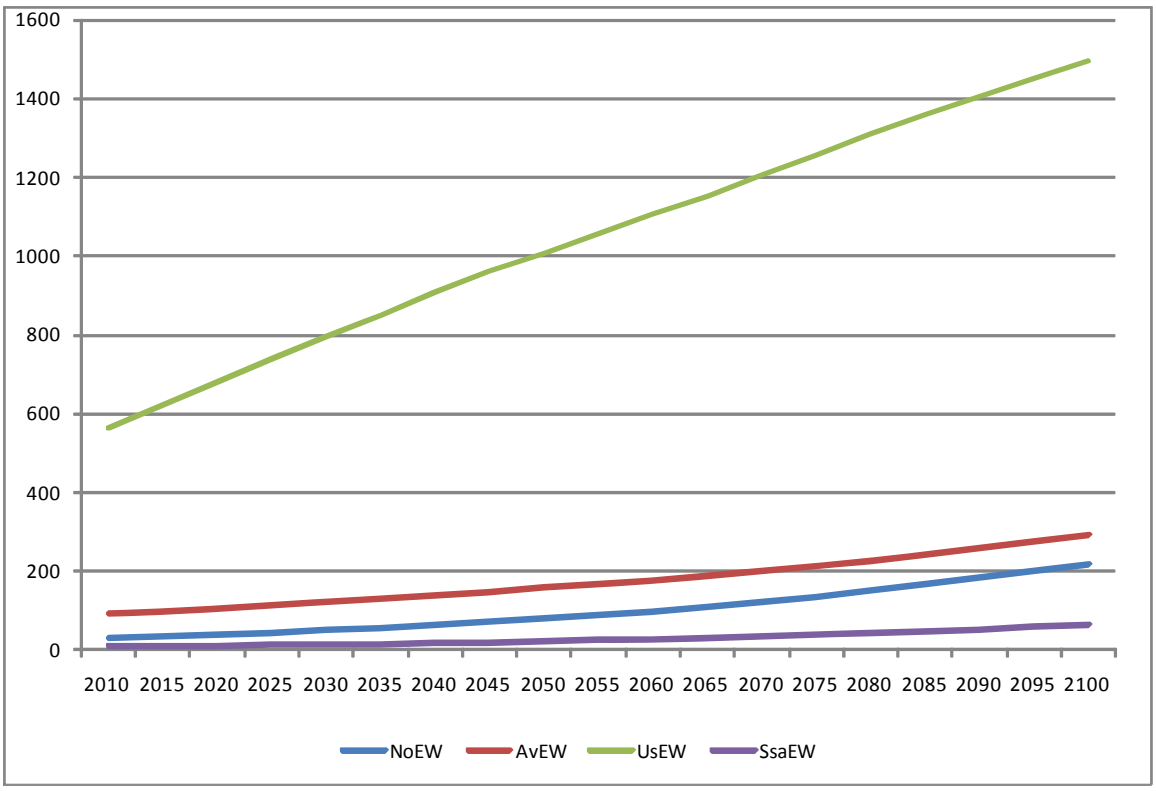

Figure 2. The social cost of carbon ($/tC) as a function of the time of emission with and without equity weights.

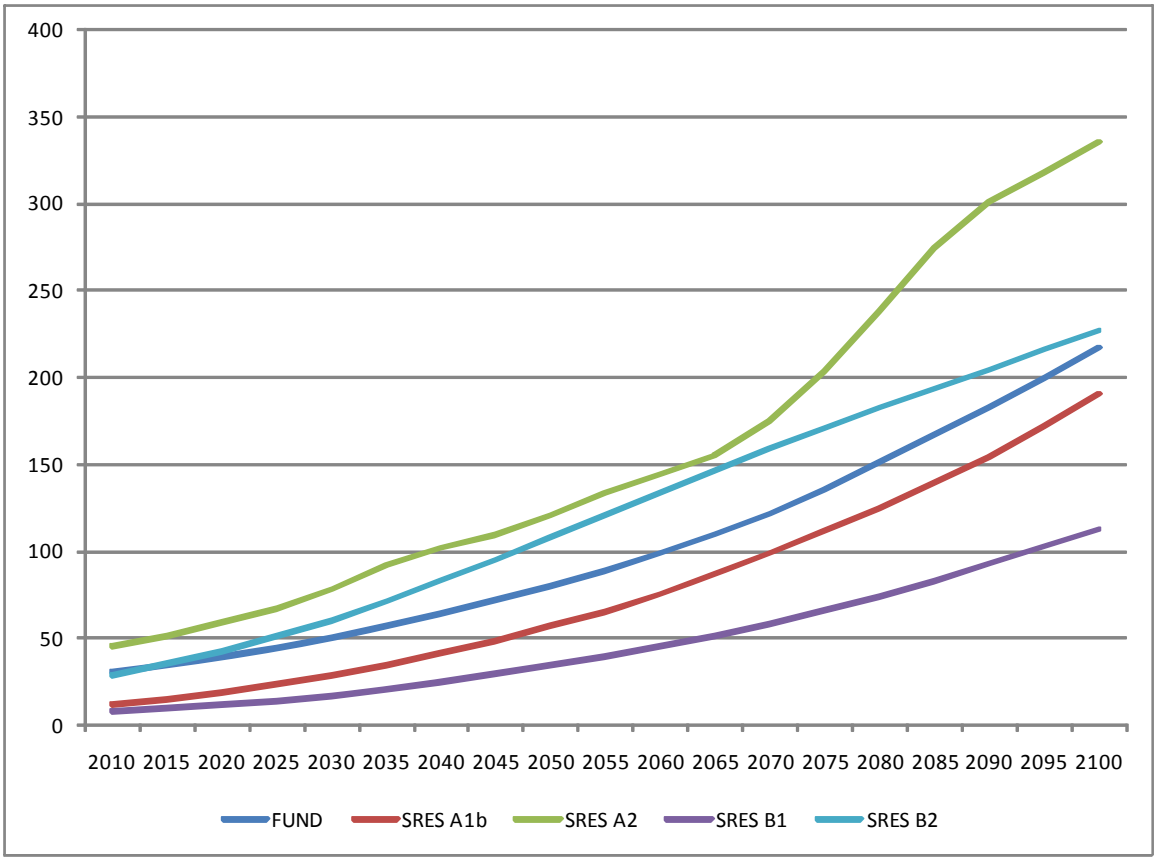

Figure 3. The social cost of carbon ($/tC) as a function of the time of emission for alternative socio-economic and emissions scenarios.

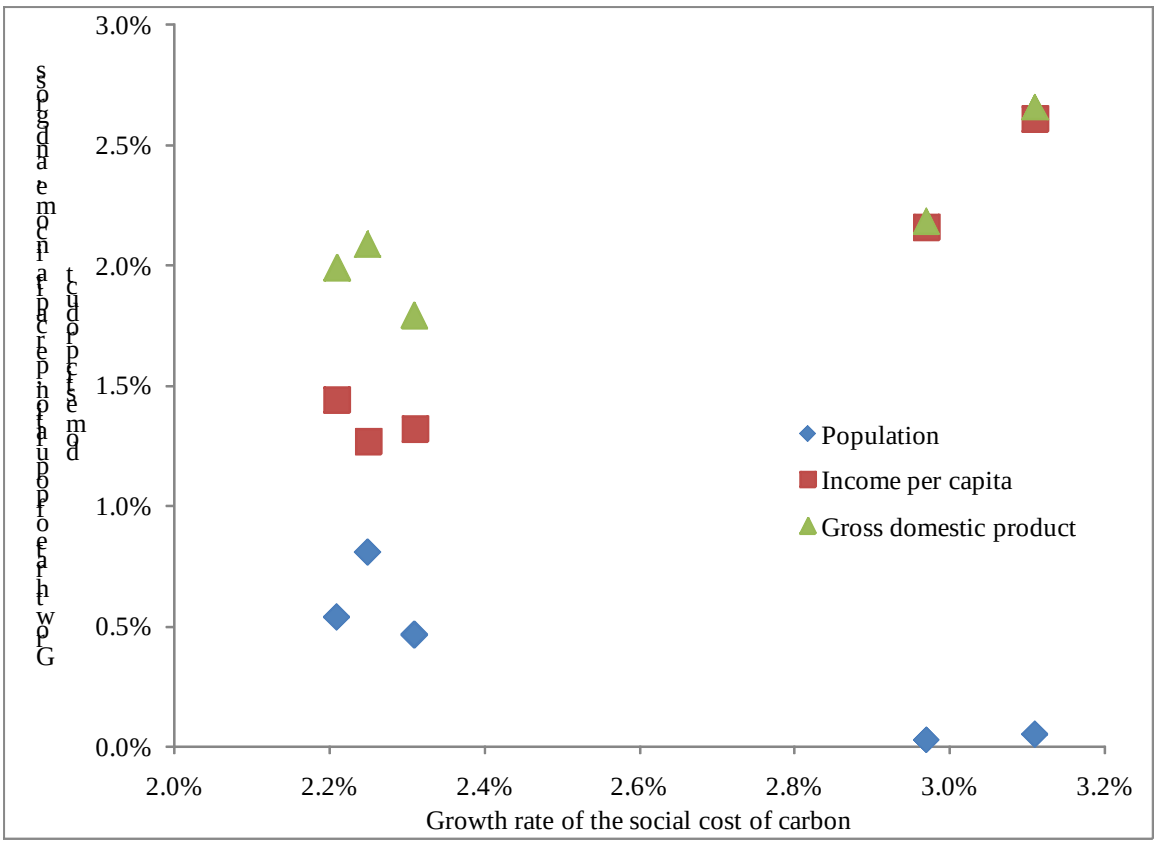

Figure 4. The 2010-2100 average annual growth rate of the social cost of carbon versus the average annual growth rates of population, per capita income, and gross domestic product.

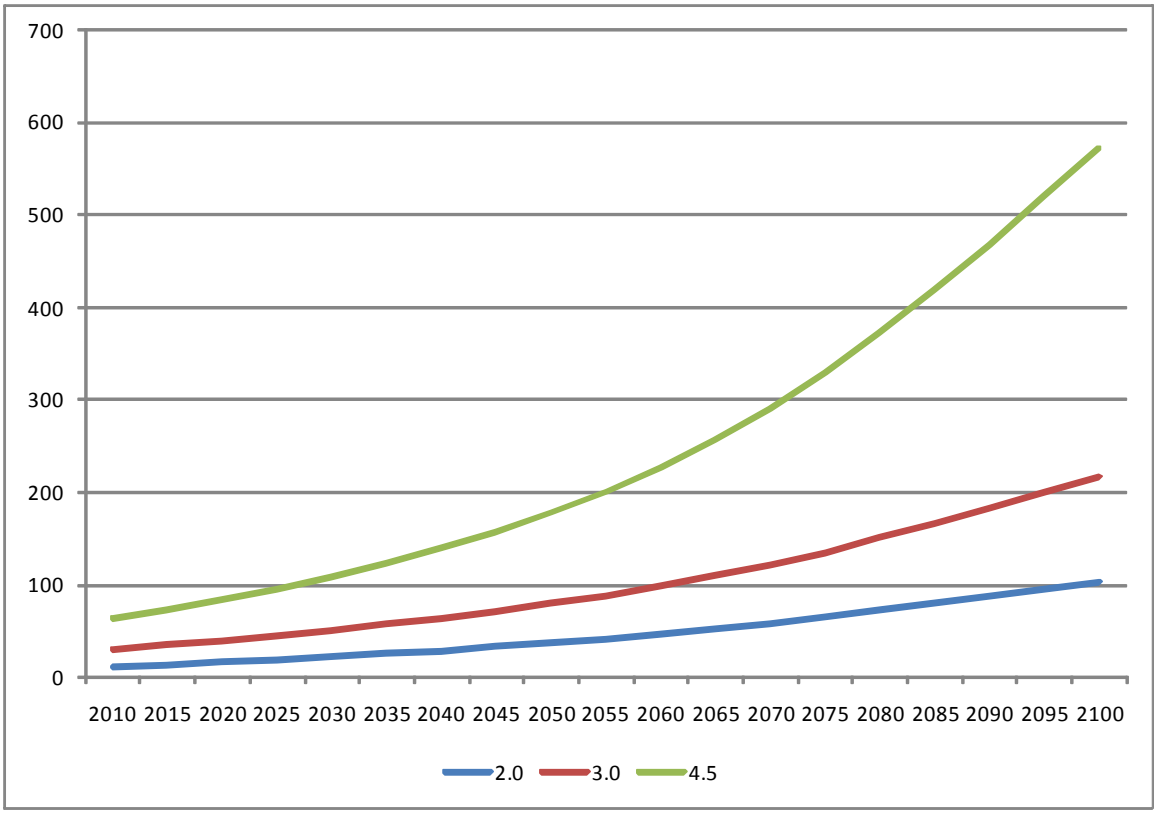

Figure 5. The social cost of carbon as a function of the time of emission for alternative climate sensitivities.

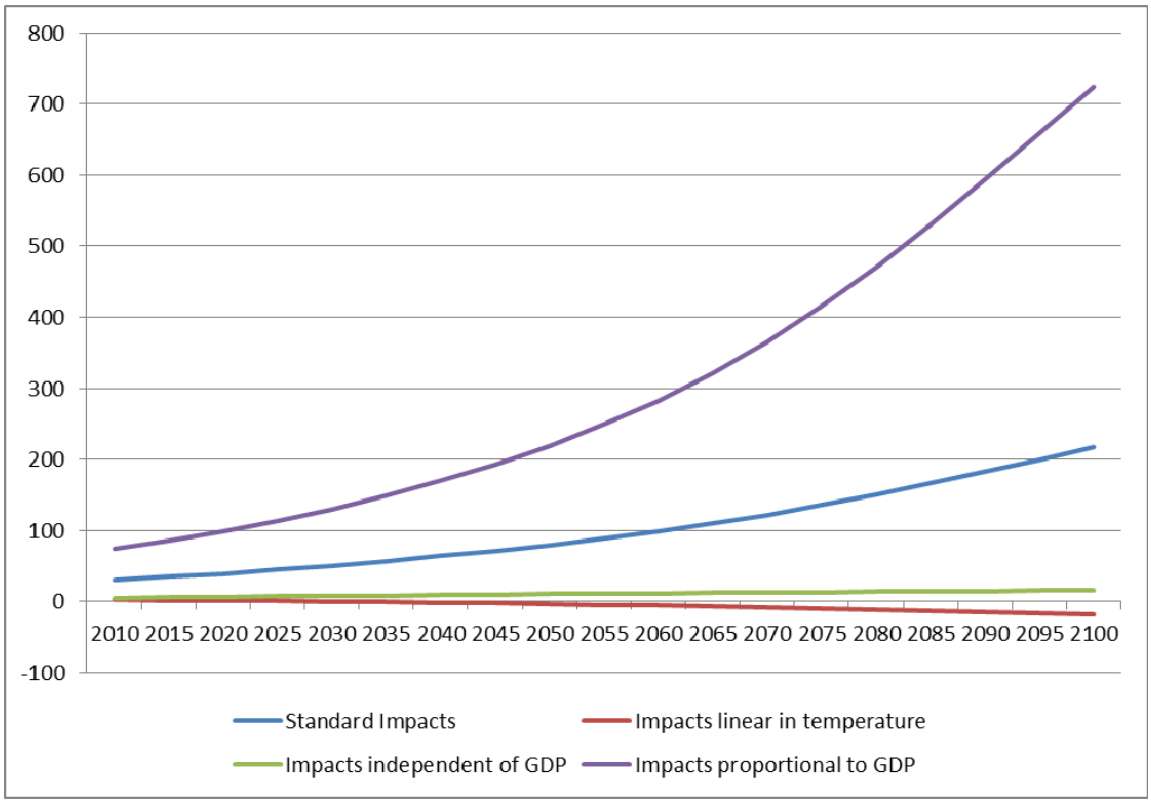

Figure 6. The social cost of carbon as a function of the time of emission with the standard model, with impact functions linear in temperature, and with impacts independent and proportional to GDP.

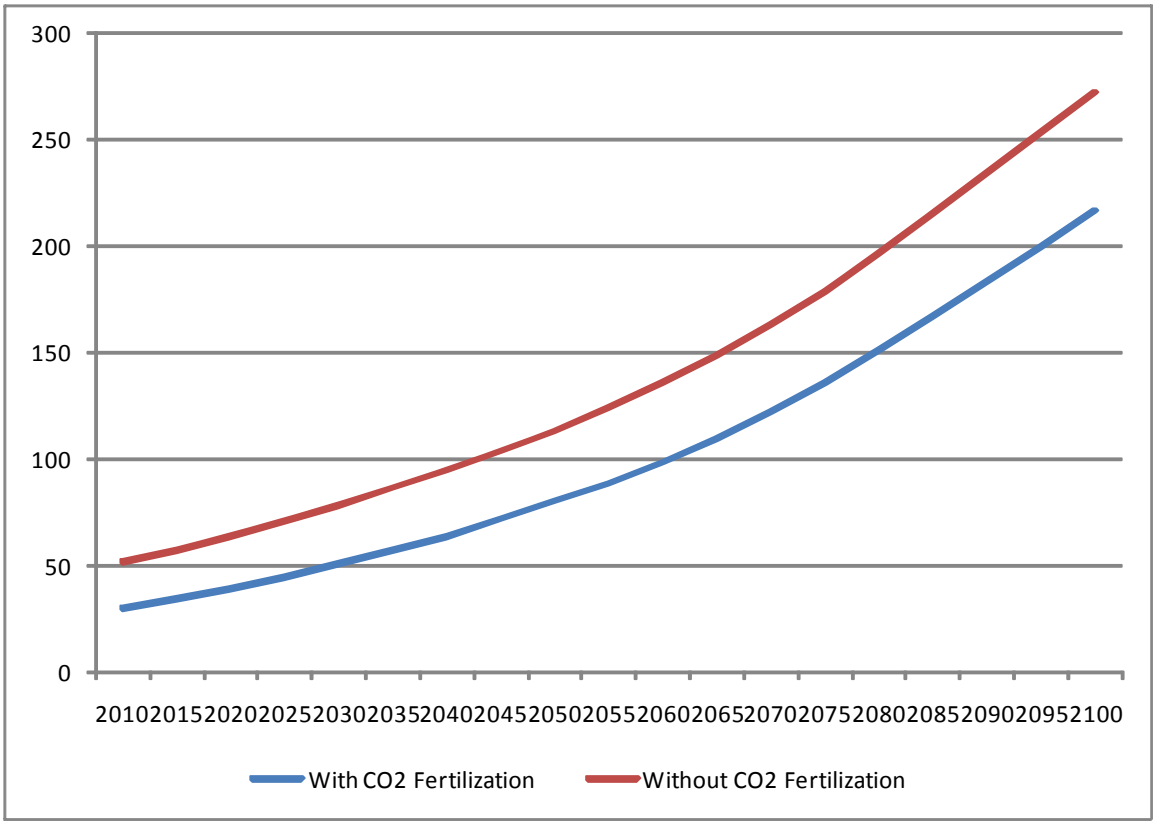

Figure 7. The social cost of carbon as a function of the time of emission with and without CO2 fertilization.

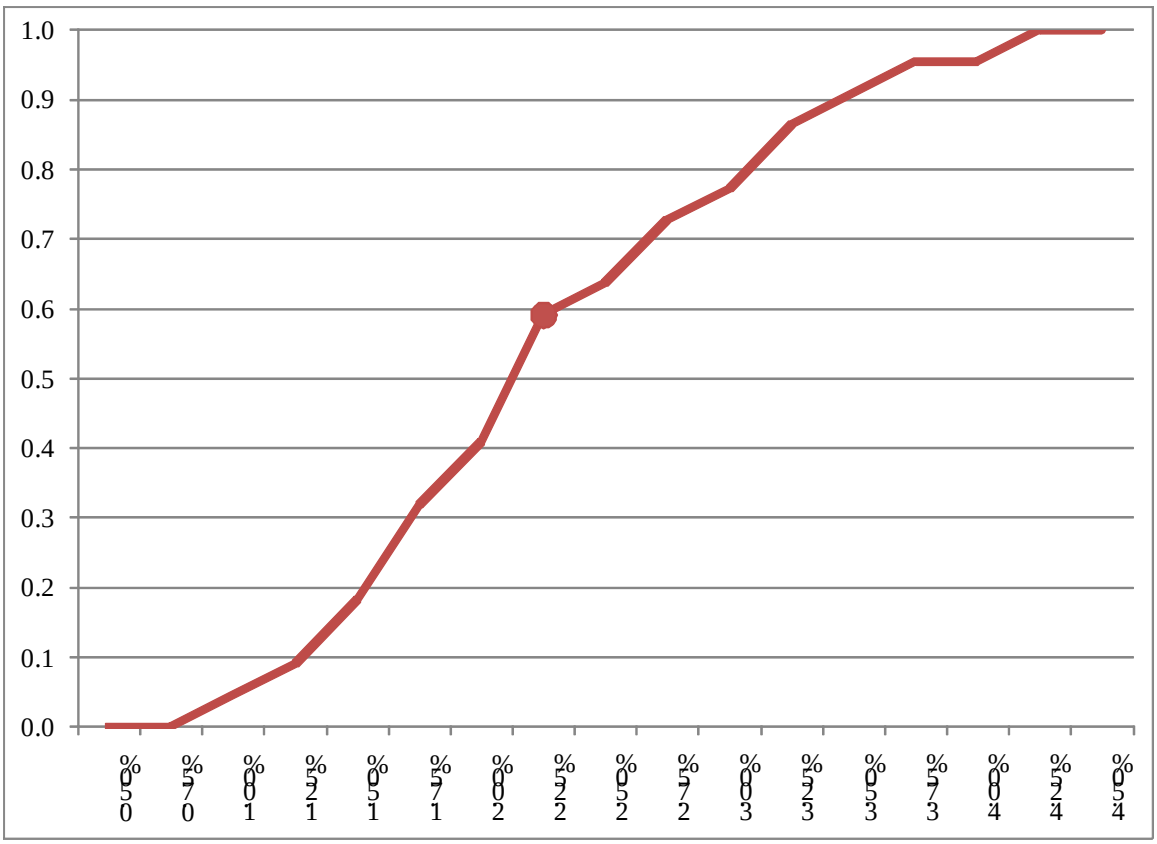

Figure 8. The cumulative density function of previous estimates of the annual growth rate of the social cost of carbon; our base estimate is indicated by the dot.