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The Social Cost of Carbon

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Abstract: This paper surveys the literature on the economic impact of climate change. Different methods have been used to estimate the impact of climate change on human welfare. Studies agree that there are positive and negative impacts. In the short term, positive impacts may dominate, but these are largely sunk. In the longer term, there are net negative impacts. Poorer people tend to be more vulnerable to climate change. There is a trade-off between development policy and climate policy. Estimated aggregate impacts are not very large, but they are uncertain and incomplete. Estimates of the marginal impacts suggest that greenhouse gas emissions should be taxed, and that the emission reduction targets announced by politicians are probably too ambitious.

Key words: Climate policy; carbon dioxide emission reduction; cost-benefit analysis

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1. Introduction

Although climate change no longer tops of the political and media agenda, it remains an important issue for which a solution remains elusive. The economic stakes are high. The European Union reckons that by 2020 $100 billion per year will be transferred from developed to developing countries (Council of the European Union 2009) for mitigation of greenhouse gas emissions and adaptation to climate change. This compares to $120 billion that was given in development aid in 2008 (OECD 2009). While energy price shocks were involved in many of the recessions in the second half of the 20th century (Hamilton 1996), climate policy promises more expensive energy. (Böhringer et al. 2009) estimate that climate policy could cost 1-4% of welfare in Europe in 2020, and (Fawcett et al. 2009) report estimates of up to 3% for the USA. Would these investments pay off?

The prime aim of climate policy is to avoid the presumably negative impacts of climate change. In this paper, I review what is known about the impacts of climate change. I review the impacts of climate change on human welfare. This includes the impacts on humans and all things that humans care about. Obviously, climate change also affects things that humans do not care about, but those matters do not influence human decisions. In the review, I ask two basic questions. What do we know? What do we not know (but would like to know)? I sketch the implications for climate policy.

I focus on the social cost of carbon, or the marginal impact of greenhouse gas emissions. This is the damage done by emitting an additional tonne of carbon dioxide, or the damage avoided by reducing emissions by one tonne. The marginal benefit is the relevant concept in optimal climate policy. A decision maker during her time in office in a single country can only hope to make a small contribution to climate policy – as it is a global problem with a time scale of centuries – so that also from this perspective, marginal benefits are what matters.

The paper proceeds as follows. Section 2 surveys the estimates of the total impact of climate. Section 3 reviews the impacts that have yet to be quantified. Section 4 analyses the marginal impacts. Section 5 concludes, and discusses implications for economic research.

2. Estimates of the Total Economic Effect of Climate Change

The first studies of the welfare impacts of climate change were done for the United States (Cline 1992;Nordhaus 1991;Smith 1996;Titus 1992). Although (Nordhaus 1991) extrapolated his U.S. estimate to the world, and (Hohmeyer and Gaertner 1992) published some global estimates, the credit for the first serious study of the global welfare impacts of climate change goes to (Fankhauser 1994;Fankhauser 1995). Table 1 lists that study and a dozen other studies of the worldwide effects of climate change.

Any study of the economic impact of climate change begins with some assumptions on future emissions, the extent and pattern of warming, and other possible aspects of climate change, such as sea level rise and changes in rainfall and storminess. The studies must then translate from climate change to economic consequences. A range of methodological approaches are possible.

(Nordhaus 1994a) interviewed a limited number of "experts"[1], asking them directly about the total economic impact.

The studies by Fankhauser (1994, 1995), (Nordhaus 1994b), (Tol 1995;Tol 2002a;Tol 2002b) use the *enumerative method*. In this approach, estimates of the "physical effects" of climate change are obtained one by one from natural science papers, which in turn may be based on some combination of climate models, impact models and laboratory experiments. The physical impacts must then each be given a price, and added up. For traded goods and services, such as agricultural products, agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value that change in farm productivity. As another example, the impact of sea level rise constitutes coastal protection and land lost, estimates of which can be found in the engineering literature; the economic input in

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[1] While these people were experts in other fields, there was no literature on the economic impacts of climate change at that time.

this case is not only the cost of dike building and the value of land, but also the decision which properties to protect. For non-traded goods and services, other methods are needed. An ideal approach might be to study how climate change affects human welfare through health and nature in each area around the world, but a series of "primary valuation" studies of this kind would be expensive and time-consuming. Thus, the monetisation of non-market climate change impacts relies on "benefit transfer," in which epidemiology papers are used to estimate effects on health or the environment, and then economic values are applied from studies of the valuation of mortality risks in other contexts than climate change.

An alternative approach (Mendelsohn et al. 2000b;Mendelsohn et al. 2000a) can be called the *statistical approach.* It is based on direct estimates of the welfare impacts, using observed variations (across space within a single country) in prices and expenditures to discern the effect of climate. Mendelsohn assumes that the observed variation of economic activity with climate over space holds over time as well; and uses climate models to estimate the future impact of climate change. Mendelsohn's estimates are done per sector for selected countries, extrapolated to other countries, and then added up, but physical modelling is avoided. Other studies (Maddison 2003;Nordhaus 2006) use versions of the statistical approach as well. Nordhaus uses empirical estimates of the *aggregate* climate impact on income across the world (per grid cell), while Maddison looks at patterns of *aggregate* household consumption (per country). Like Mendelsohn, Nordhaus and Maddison rely exclusively on observations, assuming that "climate" is reflected in incomes and expenditures – and that the spatial pattern holds over time. (Rehdanz and Maddison 2005) also empirically estimate the aggregate impact, using self-reported happiness for dozens of countries.

The enumerative approach has the advantage that it is based on natural science experiments, models and data; the results are physically realistic. However, the enumerative approach also raises concerns about extrapolation: economic values estimated for other issues are applied to climate change concerns; values estimated for a limited number of locations are extrapolated to the world; and values estimated for the recent past are extrapolated to the remote future. Tests of benefit transfer methods have shown time and again that errors from such extrapolations can be substantial (Brouwer and Spaninks 1999). But perhaps the main disadvantage of the enumerative approach is that the assumptions about adaptation may be unrealistic—as temperatures increase, presumably private and public-sector reactions would occur to both market and non-market events.

In contrast, the statistical studies rely on uncontrolled experiments. These estimates have the advantage of being based on real-world differences in climate and income, rather than extrapolated differences. Therefore, adaptation is realistically, if often implicitly, modelled. However, statistical studies run the risk that all differences between places are attributed to climate. Furthermore, the data often allow for cross-sectional studies only; and some important aspects of climate change, particularly the direct impacts of sea level rise and carbon dioxide fertilization, do not have much spatial variation.

Given that the studies in Table 1 use different methods, it is striking that the estimates are in broad agreement on a number of points – indeed, the uncertainty analysis displayed in Figure 1 reveals that no estimate is an obvious outlier. Table 1 shows selected characteristics of the published estimates. The first column of Table 1 shows the underlying assumption of long-term warming, measured as the increase in the global average surface air temperature. It is reasonable to think of these as the temperature increase in the second half of the 21st century. However, the impact studies in Table 1 are comparative static, and they impose a future climate on today's economy. One can therefore not attach a date to these estimates. The second column of Table 1 shows the impact on welfare at that future time, usually expressed as a percentage of income. For instance, (Nordhaus, William D. 94b) estimates that the impact of 3˚C global warming is as bad as losing 1.4% of income. In some cases, a confidence interval (usually at the 95 percent level) appears under the estimate; in other cases, a standard deviation is given; but the majority of studies does not report any estimate of the uncertainty. The rest of Table 1 illustrates differential effects around the world. The third column shows the percentage decrease in annual GDP of the regions hardest-hit by climate change, and the fourth column identifies those regions. The fifth column shows the percentage change in GDP for regions that are least-hurt by (or even benefit from) climate change and the final column identifies those regions.

A first area of agreement between these studies is that the welfare effect of a doubling of the atmospheric concentration of greenhouse gas emissions on the current economy is relatively small—a few percentage points of GDP. It is roughly equivalent to a year's growth in the global economy—which suggests that over a century or so, the economic loss from climate change is not all that large. However, the damage is not negligible. An environmental issue that causes a permanent reduction of welfare, lasting into the indefinite future, would certainly justify some steps to reduce such costs.

A second finding is that some estimates (Hope 2006;Mendelsohn et al. 2000b;Mendelsohn et al. 2000a;Tol 2002b) point to initial benefits of a modest increase in temperature, followed by losses as temperatures increase further. There are no estimates for a warming above 3˚C, although climate change may well go beyond that. All studies published after 1995 have regions with net gains and net losses due to global warming, while earlier studies only find net losses. Figure 1 illustrates this pattern. The horizontal axis shows the increase in average global temperature. The vertical index shows the central estimate of welfare loss. The central line shows a best-fit parabolic line from an ordinary least squares regression. Of course, it is something of a stretch to interpret the results of these different studies as if they were a time series of how climate change will affect the economy over time, and so this graph should be interpreted more as an interesting calculation than as hard analysis. But the pattern of modest economic gains due to climate change, followed by substantial losses, appears also in the few studies that report impacts over time (Mendelsohn et al. 2000b;Mendelsohn et al. 2000a;Nordhaus and Boyer 2000;Smith et al. 2001;Tol 2002b).

The initial benefits arise partly because more carbon dioxide in the atmosphere reduces "water stress" in plants and may make them grow faster (Long et al. 2006). In addition, the output of the global economy is concentrated in the temperate zone, where warming reduces heating costs and cold-related health problems. Although the world population is concentrated in the tropics, where the initial effects of climate change are probably negative, the relatively smaller size of the economy in these areas means that gains for the high-income areas of the world exceed losses in the low-income areas.

However, this pattern should be interpreted with care. Even if, initially, economic impacts may well be positive, it does not follow that greenhouse gas emissions should be subsidized. The climate responds rather slowly to changes in greenhouse gas emissions. The initial warming can no longer be avoided; it should be viewed as a sunk benefit. The fitted line in Figure 1 suggests that the turning point in terms of economic benefits occurs at about 1.1ºC warming (with a standard deviation of 0.7ºC). Policy steps to reduce emissions of greenhouse gases in the near future would begin to have a noticeable affect on climate sometime around mid-century, at just about the time that the incremental impact of climate change is negative.

Third, although greenhouse gas emissions per person are higher in high-income countries, relative impacts of climate change are greater in low-income countries (Yohe and Schlesinger 2002). Indeed, impact estimates for Sub-Saharan Africa go up to a welfare loss equivalent to the loss of a quarter of income (Table 1). The estimates are higher for several reasons. Low-income countries tend to be in tropical zones closer to the equator. They are already hotter, and their output already suffers to some extent from their higher temperatures in sectors like agriculture. Moreover, low-income countries are typically less able to adapt to climate change both because of a lack of resources and less capable institutions (Adger 2006;Alberini et al. 2006;Smit and Wandel 2006;Tol et al. 2007;Tol 2008a;Tol and Yohe 2007b;Yohe and Tol 2002). The policy implication is profound. If countries are vulnerable to climate change because they are poor, development policy may be more effective in reducing the impacts of climate change than greenhouse gas emission reduction (Schelling 1995;Tol 2005).

Fourth, estimates of the economic effects of greenhouse gas emissions have become less pessimistic over time. For the studies listed here, the estimates increase by 0.23 percent of GDP per year in which the study was done (with a standard deviation of 0.10 percent per year). There are several reasons for this change. Projections of future emissions and future climate change have become less severe over time – even though the public discourse has become shriller. The earlier studies focused on the negative impacts of climate change, whereas later studies considered the balance of positives and negatives. In addition, earlier studies tended to ignore adaptation. More recent studies include some provision for agents to change their behaviour in response to climate change. However, more recent studies also tend to assume that agents have perfect foresight about climate change, and have the flexibility and appropriate incentives to respond. Given that forecasts are imperfect, agents are constrained in many ways, and markets are often distorted (particularly in the areas that matter most for the effects of climate change such as water, food, energy, and health), recent studies of the economic effects of climate change may be too optimistic about the possibilities of adaptation and thus tend to underestimate the economic effects of climate change.

A fifth common conclusion from studies of the economic effects of climate change is that the uncertainty is vast and probably right-skewed. For example, consider only the studies that are based on a benchmark warming of 2.5ºC. These studies have an average estimated effect of climate change on average output of -0.7 percent of GDP, and a standard deviation of 1.2 percent of GDP. Moreover, this standard deviation is only about best estimate of the economic impacts, given the climate change estimates. It does not include uncertainty about future levels of greenhouse gas emissions, or uncertainty about how these emissions will affect temperature levels, or uncertainty about the physical consequences of these temperature changes. Moreover, it is quite possible that the estimates are not independent, as there are only a relatively small number of studies, based on similar data, by authors who know each other well.

Only five of the 14 studies in Table 1 report some measure of uncertainty. Two of these report a standard deviation only—which suggests symmetry in the probability distribution. Three studies report a confidence interval – of these, two studies find that the uncertainty is right-skewed, but one study finds a left-skewed distribution. Although the evidence on uncertainty here is modest and inconsistent, and I suspect less than thoroughly reliable, it seems that negative surprises should be more likely than positive surprises. While it is relatively easy to imagine a disaster scenario for climate change – for example, involving massive sea level rise or monsoon failure that could even lead to mass migration and violent conflict – it is not at all easy to argue that climate change will be a huge boost to human welfare.

Figure 1 has three alternative estimates of the uncertainty around the central estimates. First, it shows the sample statistics. This may be misleading for the reasons outlined above; note that there are only two estimates each for a 1.0˚C and a 3.0˚C global warming. Second, I re-estimated the parabola 14 times with one observation omitted. This exercise shows that the shape of the curve in Figure 1 does not depend on any single observation. At the same time, the four estimates for a 1.0˚C or 3.0˚C warming each have a substantial (but insignificant) effect on the parameters of the parabola. Third, five studies report standard deviations or confidence intervals.

Confidence intervals imply standard deviations, but because the reported intervals are asymmetric I derived two standard deviations, one for negative deviations from the mean, and one for positive deviations. I assumed that the standard deviation grows linearly with the temperature, and fitted a line to each of the two sets of five "observed" standard deviations. The result is the asymmetric confidence interval shown in Figure 1. This probably best reflects the considerable uncertainty about the economic impact of climate change, and that negative surprises are more likely than positive ones.

In other words, the level of uncertainty here is large, and probably understated—especially in terms of failing to capture downside risks. The policy implication is that reduction of greenhouse gas emissions should err on the ambitious side.

The kinds of studies presented in Table 1 can be improved in numerous ways, some of which have been mentioned already. In all of these studies, economic losses are approximated with direct costs, ignoring general equilibrium and even partial equilibrium effects.[2]

In the enumerative studies, effects are usually assessed independently of one another, even if there is an obvious overlap—for example, losses in water resources and losses in agriculture may actually represent the same loss. Estimates are often based on extrapolation from a few detailed case studies, and extrapolation is to climate and levels of development that are very different from the original case study. Little effort has been put into validating the underlying models against independent data – even though the findings of the first empirical estimate of the impact of climate change on agriculture by (Mendelsohn et al. 1994) were in stark contrast to earlier results like

[2] General equilibrium studies of the effect of climate change on agriculture have a long history (Darwin 2004;Kane et al. 1992). These papers show that markets matter, and may even reverse the sign of the initial impact estimate (Yates and Strzepek 1998). (Bosello et al. 2007) and (Darwin and Tol 2001) show that sea level rise would change production and consumption in countries that are not directly affected, primarily through the food market (as agriculture is affected most by sea level rise through land loss and saltwater intrusion) and the capital market (as sea walls are expensive to build). Ignoring the general equilibrium effects probably leads to only a small negative bias in the global welfare loss, but differences in regional welfare losses are much greater. Similarly,(Bosello et al. 2006) show that the direct costs are biased towards zero for health, that is, countries that would see their labour productivity fall (rise) because of climate change would also lose (gain) competitiveness. (Berrittella et al. 2006) also emphasize the redistribution of impacts on tourism through markets.

those of (Parry 1990), which suggests that this issue may be important. Realistic modelling of adaptation is problematic, and studies typically either assume no adaptation or perfect adaptation. Many effects are unquantified, and some of these may be large (see below). The uncertainties of the estimates are largely unknown. These problems are gradually being addressed, but progress is slow. Indeed, the list of warnings given here is similar to those in (Fankhauser and Tol 1996;Fankhauser and Tol 1997).

A deeper conceptual issue arises with putting value on environmental services. Empirical studies have shown that the willingness to pay (WTP) for improved environmental services may be substantially lower than the willingness to accept compensation (WTAC) for diminished environmental services (Horowith and McConnell 2002). The difference between WTP and WTAC goes beyond income effects, and may even hint at loss aversion and agency effects, particularly around involuntary risks. A reduction in the risk of mortality due to greenhouse gas emission abatement is viewed differently than an increase in the risk of mortality due to the emissions of a previous generation in a distant country. The studies listed in Table 1 all use willingness to pay as the basis for valuation of environmental services, as recommended by (Arrow et al. 1993). Implicitly, the policy problem is phrased as "How much are we willing to pay to buy an improved climate for our children?" Alternatively, the policy problem could be phrased as "How much compensation should we pay our children for worsening their climate?" This is a different question, and the answer would be different if the current policy makers assume that future generations would differentiate between WTP and WTAC much like the present generation does. The marginal reserves created for compensation would be larger than the marginal investment in emission reduction – which suggests that emission reduction would be preferred over compensation.

3. Missing Impacts

The effects of climate change that have been quantified and monetized include the impacts on agriculture and forestry, water resources, coastal zones, energy consumption, air quality, tropical and extratropical storms, and human health. Obviously, this list is incomplete. Even within each category, the assessment is incomplete. I cannot offer quantitative estimates of these missing impacts, but a qualitative and speculative assessment of their relative importance follows.

Many of the omissions seem to be relatively small compared to those items that have been quantified. Among the negative effects, for example, studies of the effect of sea level rise on coastal zones typically omit costs of saltwater intrusion in groundwater (Nicholls and Tol 2006). Increasing water temperatures would increase the costs of cooling power plants (Szolnoky et al. 1997). Redesigning urban water management systems, be it for more of less water, would be costly (Ashley et al. 2005), as would implementing safeguards against increased uncertainty about future circumstances. Ocean acidification may harm fisheries (Kikkawa et al. 2004).

The list of relatively small missing effects would also include effects that are probably positive. Higher wind speeds in the mid-latitudes would decrease the costs of wind and wave energy (Breslow and Sailor 2002). Less sea ice would improve the accessibility of Arctic harbours, would reduce the costs of exploitation of oil and minerals in the Arctic, and might even open up new transport routes between Europe and East Asia (Wilson et al. 2004). Warmer weather would reduce expenditures on clothing and food, and traffic disruptions due to snow and ice (Carmichael et al. 2004).

Some missing effects are mixed. Tourism is an example. Climate change may well drive summer tourists towards the poles and up the mountains, which amounts to a redistribution of tourist revenue (Berrittella et al. 2006). Other effects are simply not known. Some rivers may see an increase in flooding, and others a decrease (Kundzewicz et al. 2005;Svensson et al. 2005).

These small unknowns, and doubtless others not identified here, are worth some additional research, but they pale in comparison to the big unknowns: extreme climate scenarios, the very long term, biodiversity loss, the possible effects of climate change on economic development and even political violence.

Examples of extreme climate scenarios include an alteration of ocean circulation patterns—such as the Gulf Stream that brings water north from the equator up through the Atlantic Ocean (Marotzke 2000). This may lead to a sharp drop in temperature in and around the North Atlantic. Another example is the collapse of the West-Antarctic Ice Sheet (Vaughan 2008;Vaughan and Spouge 2002), which would lead to sea level rise of 5-6 meters in a matter of centuries. A third example is the massive release of methane from melting permafrost (Harvey and Zhen 1995), which would lead to rapid warming worldwide. Exactly what would cause these sorts of changes or what effects they would have are not at all well-understood, although the chance of any one of them happening seems low. But they do have the potential to happen relatively quickly, and if they did, the costs could be substantial. Only a few studies of climate change have examined these issues. (Nicholls et al. 2008) find that the impacts of sea level rise increase ten-fold should the West-Antarctic Ice Sheet collapse, but the work of (Olsthoorn et al. 2008) suggests that this may be too optimistic as Nicholls et al. (2008) may have overestimated the speed with which coastal protection can be build. (Link and Tol 2004) estimate the effects of a shutdown of the thermohaline circulation. They find that the resulting regional cooling offsets but does not reverse warming, at least over land. As a consequence, the net economic effect of this particular change in ocean circulation is *positive*.

Another big unknown is the effect of climate change in the very long term. Most static analyses examine the effects of doubling the concentration of atmospheric CO_2; most studies looking at effects of climate change over time stop at 2100. Of course, climate change will not suddenly halt in 2100. In fact, most estimates suggest that the negative effects of climate change are growing, and even accelerating, in the years up to 2100 (cf. Figure 1). It may be that some of the most substantial benefits of addressing climate change occur after 2100, but studies of climate change have not looked seriously at possible patterns of emissions and atmospheric concentrations of carbon after 2100, the potential physical effects on climate, nor the monetary value of those impacts. One may argue that impacts beyond 2100 are irrelevant because of time discounting, but this argument would not hold if the impacts grow faster than the discount rate – because of the large uncertainty, this cannot be excluded.

Climate change could have a profound impact on biodiversity (Gitay et al. 2001), not only through changes in temperature and precipitation, but in the ways climate change might affect land use and nutrient cycles, ocean acidification, and the prospects for invasion of alien species into new habitats. Economists have a difficult time analyzing this issue. For starters, there are few quantitative studies of the effects of climate change on ecosystems and biodiversity. Moreover, valuation of ecosystem change is difficult, although some methods are being developed (Champ et al. 2003). These methods are useful for marginal changes to nature, but may fail for the systematic impact of climate change. That said, valuation studies have consistently shown that, although people are willing to pay something to preserve or improve nature, most studies put the total willingness to pay for nature conservation at substantially less than 1 percent of income (Pearce and Moran 1994). Unless scientists and economists develop a rationale for placing a substantially higher cost on biodiversity, it will not fundamentally alter the estimates of total costs of climate change.

A cross-sectional analysis of per capita income and temperature may suggest that people are poor because of the climate (Acemoglu et al. 2001;Gallup et al. 1999;Masters and McMillan 2001;Nordhaus 2006;van Kooten 2004), although others would argue that institutions are more important than geography (Acemoglu et al. 2002;Easterly and Levine 2003). There is an open question about the possible effects of climate change on annual rates of economic growth. For example, one possible scenario is that low-income countries, which are already poor to some extent because of climate, will suffer more from rising temperatures and have less ability to adapt, thus dragging their economies down further. (Fankhauser and Tol 2005) argue that only very extreme parameter choices would imply such a scenario. In contrast, (Dell et al. 2008) find that climate change would slow the *annual* growth rate of poor countries by 0.6 to 2.9 per cent points. Accumulated over a century, this effect would dominate all earlier estimates of the economic effects of climate change. However, Dell et al. (2008) have only a few explanatory variables in their regression, so their estimate may suffer from specification or missing variable bias; they may also have confused weather variability with climate change. One can also imagine a scenario in which climate change affects health, particularly the prevalence of malaria and diarrhoea, in a way that affects long-term economic growth (Galor and Weil 1999;Tang et al. 2009); or in which climate-change-induced resource scarcity intensifies violent conflict (Tol and Wagner;Zhang et al. 2006;Zhang et al. 2007) and affect long-term growth rates through that mechanism (Butkiewicz and Yanikkaya 2005). These potential channels have not been modelled in a useful way. But the key point here is that if climate change affects annual rates of growth for a sustained period of time, such effects may dominate what was calculated in the total effects studies shown earlier in Table 1.

Besides the known unknowns described above, there are probably unknown unknowns too. For example, the direct impact of climate change on labour productivity has never featured on any list of “missing impacts”, but (Kjellstrom et al. 2010) show that it may well be substantial.

The “missing impacts” are a reason for concern and further emphasize that climate change may spring nasty surprises. This justifies greenhouse gas emission reduction beyond that recommended by a cost-benefit analysis under quantified risk. The size of the “uncertainty premium” is a political decision. However, one should keep in mind that there is a history of exaggeration in the study of climate change impacts. Early research pointed to massive sea level rise (Schneider and Chen 1980), millions dying from infectious diseases (Haines and Fuchs 1991) and widespread starvation (Hohmeyer and Gaertner 1992). Later, more careful research has dispelled these fears.

4. Estimates of the Marginal Cost of Greenhouse Gas Emissions

The marginal damage cost of carbon dioxide, also known as the “social cost of carbon,” is defined as the net present value of the incremental damage due to a small increase in carbon dioxide emissions. For policy purposes, the marginal damage cost (if estimated along the optimal emission trajectory) would be equal to the Pigouvian tax that could be placed on carbon, thus internalizing the externality and restoring the market to the efficient solution.

A quick glance at the literature suggests that there are many more studies of the marginal cost of carbon than of the total cost of climate change. Table 1 has 13 studies and 14 estimates; in contrast, (Tol 2009b) reports 59 studies with 292 estimates. Since then, two studies with 19 estimates appeared. Some of the total cost estimates (Maddison 2003;Mendelsohn et al. 2000b;Mendelsohn et al. 2000a;Nordhaus 2006;Rehdanz and Maddison 2005) have yet to be used for marginal cost estimation. Therefore, the over 300 estimates of the social cost of carbon are based on nine estimates of the total impact of climate change. The empirical basis for the size of an optimal carbon tax is much smaller than is suggested by the number of estimates.

How can nine studies of total economic cost of climate change yield more than 300 estimates of marginal cost? Remember that the total cost studies are comparative static, and measure the economic cost of climate change in terms of a reduction in welfare below its reference level. This approach to describing total costs can be translated into marginal costs of current emissions in a number of ways. The rate at which future benefits (and costs) are discounted is probably the most important source of variation in the estimates of the social cost of carbon. The large effect of different assumptions about discount rates is not surprising, given that the bulk of the avoidable effects of climate change is in the distant future. Differences in discount rates arise not only from varying assumptions about the rate of pure time preference, the growth rate of per capita consumption, and the elasticity of marginal utility of consumption.[3] Some more recent studies have also analyzed variants of hyperbolic discounting, where the rate of discount falls over time.

However, there are other reasons why two studies with identical estimates of the total economic costs of climate change, expressed as a percent of GDP at some future date, can lead to very different estimates of marginal cost. Studies of the marginal damage costs of carbon dioxide emissions can be based on different projections of CO_2 emissions, different representations of the carbon cycle, different estimates of the rate of warming, and so on. Alternative population and economic scenarios also yield different estimates, particularly if vulnerability to climate change is assumed to change with a country or region's development.

For example, the estimate of (Nordhaus 1991) of the total welfare loss of a 3.0˚C warming is 1.3% of GDP. In order to derive a marginal damage cost estimate from this, you would need to assume when in the future 3.0˚C would occur, and whether damages are linear or quadratic or some other function of temperature (and precipitation et cetera). And then the future stream of incremental damages due to today's emissions needs to be discounted back to today's value.

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[3] The elasticity of marginal utility with respect to consumption plays several roles. It serves as a measure of risk aversion. It plays an important role in the discount rate (Ramsey 1928), as it also partly governs the substitution of future and present consumption. Furthermore, this parameter drives the trade-offs between differential impacts across the income distribution, both within and between countries. Although conceptually distinct, all climate policy analyses that I am aware of use a single numerical value (Atkinson et al. 2009;Saelen et al. 2008). The reason is simply that although these distinctions are well-recognized, welfare theorists have yet to find welfare and utility functions that make the necessary distinctions and can be used in applied work.

Marginal cost estimates further vary with the way in which uncertainty is treated (if it is recognized at all). Marginal cost estimates also differ with how regional effects of climate change are aggregated. Most studies add monetary effects for certain regions of the world, which roughly reflects the assumption that emitters of greenhouse gases will compensate the victims of climate change. Other studies add utility-equivalent effects – essentially assuming a social planner and a global welfare function. In these studies, different assumptions about the shape of the global welfare function can imply widely different estimates of the social cost of carbon (Anthoff et al. 2009;Fankhauser et al. 1997;Fankhauser et al. 1998).

Table 2 shows some characteristics of a meta-analysis of the published estimates of the social cost of carbon. Just looking at the distribution of the medians or modes of these studies is inadequate, because it does not give a fair sense of the uncertainty surrounding these estimates – it is particularly hard to discern the right tail of the distribution which may dominate the policy analysis (Tol 2003;Tol and Yohe 2007a;Weitzman 2009a;Weitzman 2009b). Because there are many estimates of the social cost of carbon, this can be done reasonably objectively. (The same would not be the case for the total economic impact estimates.) Thus, the idea here is to use one parameter from each published estimate (the mode) and the standard deviation of the entire sample—and then to build up an overall distribution of the estimates and their surrounding uncertainty on this basis using the methodology in (Tol 2008b).[4] The results are shown in Table 2.

Table 2 reaffirms that the uncertainty about the social costs of climate change is very large. The mean estimate in these studies is a marginal cost of carbon of $177 per metric tonne of carbon, but the modal estimate is only $49/tC. Of course, this divergence suggests that the mean estimate is driven by some very large estimates—

[4] I fitted a Fisher-Tippett distribution to each published estimate using the estimate as the mode and the *sample* standard deviation. The Fisher-Tippett distribution is the only two-parameter, fat-tailed distribution that is defined on the real line. A few published estimates are negative, and given the uncertainties about risk, fat-tailed distributions seem appropriate (Tol 2003;Weitzman 2009b). The joint probability density function follows from addition, using weights that reflect the age and quality of the study as well as the importance that the authors attach to the estimate – some estimates are presented as central estimates, others as sensitivity analyses or upper and lower bounds.

and indeed, the estimated social cost at the 95th percentile is $669/tC. At the same time, a quarter of the probability mass is below zero.

This large divergence is partly explained by the use of different pure rates of time preference in these studies. Table 2 divides up the studies into three subsamples which use the same pure rate of time preference. A higher rate of time preference means that the costs of climate change incurred in the future have a lower present value, and so for example, the sample mean social cost of carbon for the studies with a 3 percent rate of time preference is $19/tC, while it is $276/tC for studies that choose a zero percent rate of time preference. But these columns also show that even when the same discount rate is used, the variation in estimates is large. The means are pulled up by some studies with very high estimated social costs.[5] This effect is stronger for lower discount rates. Table 2 shows that the estimates for the whole sample are dominated by the estimates based on lower discount rates.

Table 2 also splits the sample into studies that were peer-reviewed and studies that were not (yet). The mean estimate of the social cost of carbon is $80/tC in the peer-reviewed literature, and $296/tC in the gray literature. The range of estimates is much larger in the gray literature. This suggests that the more dramatic estimates of the impact of climate change are of lower quality.

Table 2 further splits the sample into studies that used equity weighting – that is, corrected for the fact that a dollar to a poor woman is not the same as a dollar to a rich woman – and studies that simply added dollar estimates of the impacts in different countries. Although equity weighting almost always increases the estimate of the (marginal) impact of climate change, we find that the mean estimate of the social cost of carbon is $177/tC with equity weighting against $168/tC without. Table 2 also

[5] Some readers may wonder why the estimates with a discount rate of zero percent don't look all that substantially higher than the estimates with a discount rate of 1%. The main reason is that most estimates are (inappropriately) based on a finite time horizon. With an infinite time horizon, the social cost of carbon would still be finite, because fossil fuel reserve are finite and the economy would eventually equilibrate with the new climate, but the effect of the zero discount rate would be more substantial. For the record, there is even one estimate (Hohmeyer and Gaertner 1992) based on a zero consumption discount rate (Davidson 2006;Davidson 2008) and thus a *negative* pure rate of time preference.

splits the sample into studies that report the mean social cost of carbon (typically estimated using a Monte Carlo analysis) and studies that ignore uncertainty and report a best guess value. Again, one would expect that, since the uncertainty is large and right-skewed, the average mean would be greater than the average best guess. However, Table 2 reveals that the average social cost of carbon is $68/tC with uncertainty and $206/tC without. The reason for these unexpected results is as follows. Equity-weighting and uncertainty analysis are only done with the more sophisticated models, which tend to produce lower estimates of the social cost of carbon.

Table 2 splits the sample into studies from before 1995 (Pearce et al. 1996), between 1995 and 2001, and after 2001 (Smith et al. 2001). The mean estimate of the social cost of carbon fell from $299/tC in the early studies to $113/tC in the latest studies. The standard deviation fell from $522/tC to $153/tC. This suggests that estimates of the impact of climate change have become less dramatic over time, contrary to the assertions of (Schneider et al. 2007). The falling uncertainty suggests progress in our understanding of the impacts of climate change.

Finally, Table 2 splits the sample into studies (co-)authored by Chris Hope, William Nordhaus, Richard Tol, and others. Together, the three named authors contributed 238 of the 311 estimates. Nordhaus is the most optimistic of the three, with a mean social cost of carbon of $35/tC, followed by Tol ($59/tC) and Hope ($77/tC). Others are on average more pessimistic than the three most published authors in this field, with a mean estimate of $266/tC.

Table 2 shows univariate sample splits. The suggested trends may be because of a change in composition. For example, a false impression of waning pessimism about climate change would be created if later studies tend to use higher discount rates. I therefore estimated a multivariate regression. The results are given in Table 3, for both a simple regression and a weighted regression using author preferences[6]. Table 3 confirms Table 2 in some regards. A lower discount rate means a higher social cost of

[6] Some estimates are favoured by the authors, while other estimates are presented as a sensitivity analysis or for replication purposes.

carbon, and peer-reviewed estimates are less pessimistic. Older studies are more pessimistic. Equity weighting and uncertainty do not significantly affect the estimated social cost of carbon. Estimates by Hope and Nordhaus are significantly higher than estimates by others, but only if the estimates are weighted.

Table 2 shows that a large share of the estimates of the social cost of carbon was published by the same, small group of people. One may therefore suspect that the meta-analysis suffers from confirmation bias. Figure 2 provides a graphical test for studies that use a pure rate of time preference of 3% per year (the largest subsample). Figure 2 plots the estimates as a function of the year of publication. It also shows the mean, the 5%ile and the 95%ile of the previously published studies – that is, the mean and 90% confidence interval for, say, 2006 is based on all estimates published before 2006. Figure 2 shows that newer studies regularly challenge the conventional wisdom. Indeed, the confidence interval is widening over time, rather than narrowing. Confirmation bias is not something to worry about in this field.

Although Table 2 reveals a large estimated uncertainty about the social cost of carbon, there is reason to believe that the actual uncertainty is larger still. First of all, the social cost of carbon derives from the total economic impact estimates – and I argue above that their uncertainty is underestimated too. Second, the estimates only contain those impacts that have been quantified and valued – and I argue above that some of the missing impacts have yet to be assessed because they are so difficult to handle and hence very uncertain. Third, although the number of researchers who published marginal damage cost estimates is larger than the number of researchers who published total impact estimates, it is still a reasonably small and close-knit community who may be subject to group-think, peer pressure and self-censoring.

To place these estimated costs of carbon in context, the current price of CO2 emission permits in the European Trading Scheme is \$79/tC. A carbon tax in the range of \$50-\$100 per metric tonne of carbon would mean that new electricity generation capacity would be carbon-free, be it wind or solar power or coal with carbon capture and storage (Weyant et al. 2006). In contrast, it would take a much higher carbon tax to de-carbonize transport, as biofuels, batteries and fuel cells are very expensive still (Schaefer and Jacoby 2005;Schaefer and Jacoby 2006). The results from the latest modelling comparison exercise of the Energy Modeling Forum (Clarke et al. 2009) suggest that a global carbon tax of 374 (56-966) $/tC is needed in 2020[7] to stabilise atmospheric concentrations of greenhouse gases at 450 ppm CO_{2eq}, so that there is an even chance of meeting the EU target of 2°C warming (Meinshausen 2006). For 550 ppm CO_{2eq}, a 2020 tax of 85 (16-185) $/tC would be sufficient. For 650 ppm CO_{2eq}, 30 (2-74) $/tC is enough. Comparing these numbers to those in Table 2 would suggest an optimal stabilisation target between 550 and 650 ppm CO_{2eq}.

6. Discussion and conclusion

This paper argues four things, supported by literature review rather than primary analysis. First, although climate change has positive as well as negative impacts, the negative impacts dominate particularly for that part of climate change that can be influenced by present and future policy. Greenhouse gas emissions are a negative externality, therefore, and should be regulated. Second, the impacts of climate change fall primarily on poorer countries, and poverty is one of the main causes for this disproportionate vulnerability. This implies that a climate policy that negatively affects economic development may well have a perverse impact; and that development policy is a viable alternative to climate policy. Third, the quantified impacts do not justify claims that climate change is the largest problem of humankind or the largest environmental problem of the 21st century. Impact estimates are incomplete. Claims of impending disaster are speculative. Fourth, estimates of the social cost of carbon or the Pigou tax are highly uncertain and very sensitive to attitudes towards the distant future, faraway lands, and remote probabilities.

(Nordhaus 1977) was the first to argue the economic case for greenhouse gas emission reduction. More than thirty years later, that case still stands and it is much better substantiated. Although the literature cautions against overly ambitious and misdirected climate policy, there is only soft guidance on what would constitute the

[7] This carbon tax would rise with the rate of interest.

right or optimal level of a carbon tax. This paper is therefore a call for both emission reduction and further research.

There are only few studies on the total impact of climate change. The number of authors is lower, and can be grouped into a UCL group and a Yale one.[8] Most fields are dominated by a few people and fewer schools, but dominance in this field is for want of challengers. The impact of this is unknown. This situation is worrying. The body of evidence is incommensurate with the urgency of policy making. The reasons for the dearth of research include:

lack of funding – this work is too applied for funding by academic sources, while applied agencies dislike the typical results and pre-empt embarrassment by not funding economic impact estimates;

lack of daring – this research requires making many, often questionable assumptions, and taking on well-entrenched incumbents; and

lack of reward – the economics profession frowns on applied research in general and interdisciplinarity in particular.

It does not help that some people argue that climate policy is too complicated for cost-benefit analysis (Nelson 2008;Nelson 2009;van den Bergh 2004) or that monetary valuation is unethical (Ackerman 2008;Spash 2007). As these authors do not offer alternative methods of policy analysis, they essentially place climate policy beyond reason, in the domain of belief. It would be better to improve methods and expand data.

Attitudes towards uncertainty are often measured by the rate of risk aversion (Pratt 1964), or the elasticity of marginal utility with respect to consumption. The same parameter plays an important role in the (Ramsey 1928) discount rate, as it also partly governs the substitution of future and present consumption. Furthermore, this parameter drives the trade-offs between differential impacts across the income distribution, both within and between countries (Bergson 1938;Bergson 1954). The

[8] Nordhaus and Mendelsohn are colleagues and collaborators; Fankhauser, Maddison and Tol all worked with David Pearce and one another; Rehdanz was a student of Maddison and Tol.

consumption elasticity of marginal utility thus plays four roles. Although conceptually distinct, climate policy analyses tend to a single numerical value (Atkinson et al. 2009;Ha-Duong and Treich 2004). The reason for this is simple. It is well known that consumption smoothing over time and risk aversion are different things, and different again from inequity aversion – and that attitudes towards income gaps are different within and between jurisdictions (Amiel et al. 1999). Despite considerable research, welfare theorists have yet to find welfare and utility functions that make the necessary distinctions and can be used in applied work (Epstein and Zin 1989;Kreps and Porteus 1979). Climate change adds urgency to solving these theoretical problems.

There is a similar problem with population. Standard welfare functions work fine if population growth is exogenous, but produce peculiar and undesirable results if population is endogenous (Blackorby and Donaldson 1984). As climate change affects mortality and migration, population is endogenous to climate policy. A standard welfare function such as $W = P\ln(C/P)$, with W welfare, P population and C total consumption, would put a premium on migration from poor to rich countries and would thus encourage sea level rise and discourage coastal protection. As above, this problem is well recognised in welfare theory, but a practical solution has yet to be found.

In short, we know enough about the impacts of climate change to justify greenhouse gas emission reduction. To gain more confidence in our policy advice, more research is needed in both applied and theoretical economics.

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Table 3. Regression results; dependent variable: social cost of carbon

	Unweighted			Weighted		
	Coefficient	Std. Error		Coefficient	Std. Error	
C	14,485	4,693	***	24,784	4,767	***
Peer	-118	33	***	-159	31	***
3% PRTP	-109	35	***	-135	35	***
1% PRTP	-54	36		-121	39	***
0% PRTP	167	42	***	112	50	**
Equity	54	33		65	37	*
Uncertainty	26	29		-8	33	
Hope	79	53		135	50	***
Nordhaus	93	58		214	84	**
Tol	-108	62	*	-1	81	
Year	-7	2	***	-12	2	***
Adj. R^2	0.144			0.189		
Std.Err.	198			97		

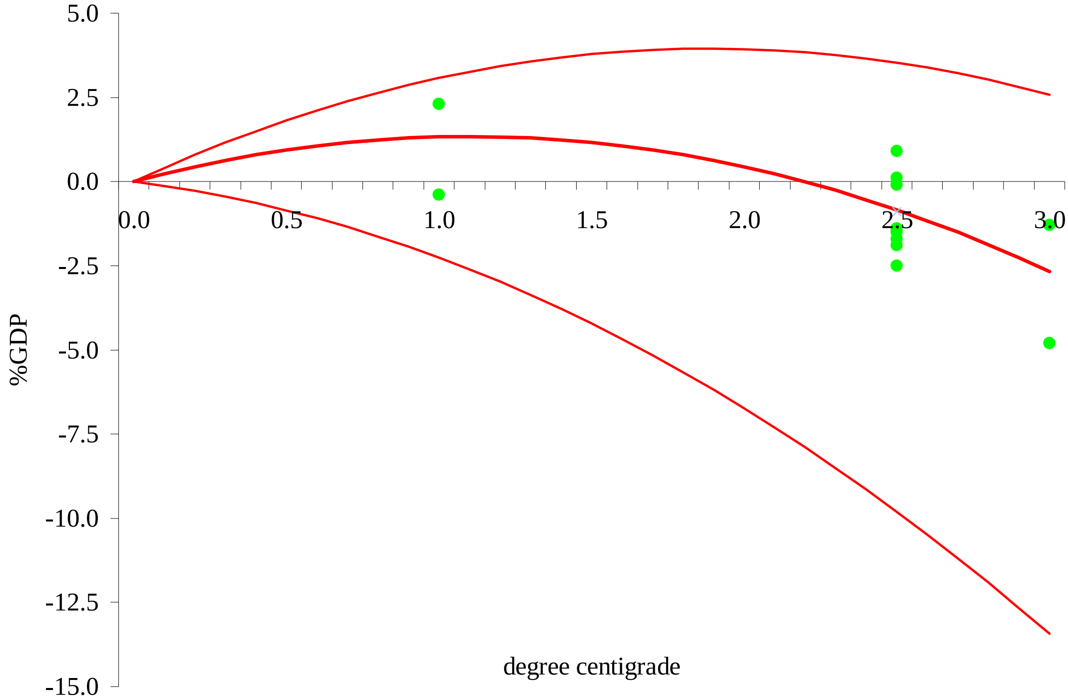

Figure 1. The 14 estimates of the global economic impact of climate change, expressed as the welfare-equivalent income loss, as a functions of the increase in global mean temperature relative to today. The green dots represent the estimates (cf. Table 1). The central red line is the least squares fit to the 14 observations: D = 2.46 (1.25) T – 1.11 (0.48) T^2, R^2 = 0.51, where D denotes impact and T denotes temperature; standard deviations are between brackets. The red outer two lines are the 95% confidence interval, where the standard deviation is the least squares fit to the 5 reported standard deviations or half confidence intervals (cf. Table 1): $S_{optimistic}$ = 0.87 (0.28) T, R^2 = 0.70, $S_{pessimistic}$ = 1.79 (0.87) T, R^2 = 0.51 where S is the standard deviation. Source: After (Tol 2009a)

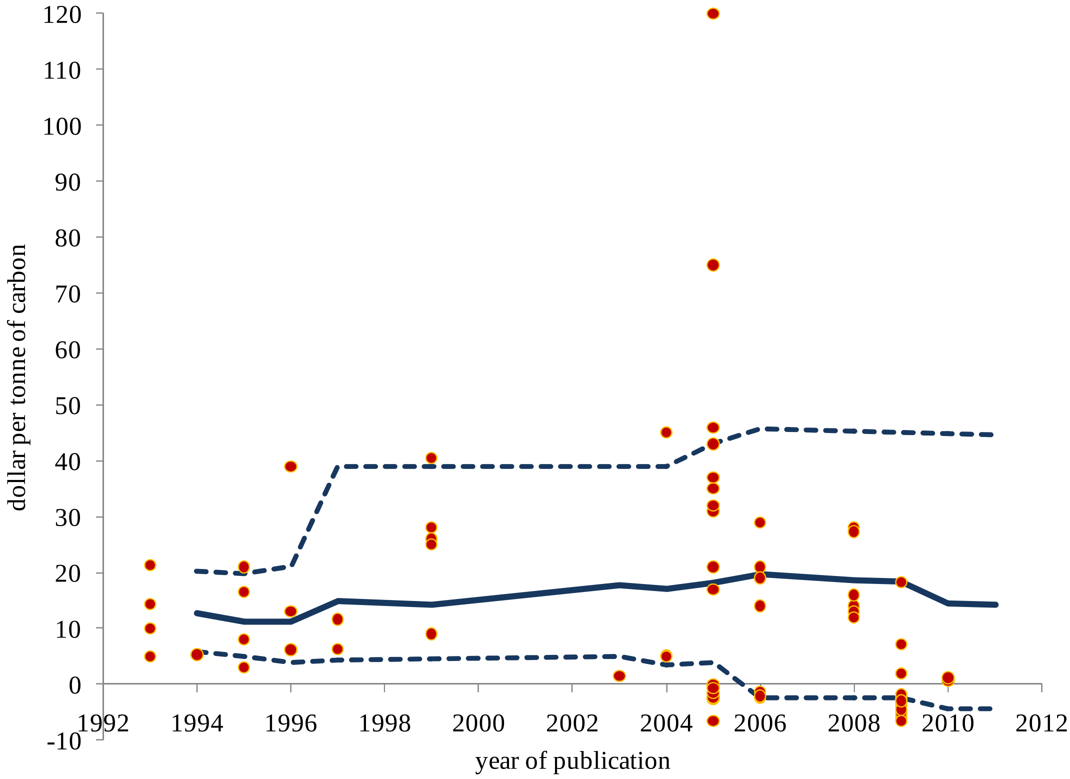

Figure 2. Estimates of the social cost of carbon for a pure rate of time preference of 3% per year as a function of the year of publication; dots are individual estimates; the solid (dotted) line is the mean (90% confidence interval) of previously published studies.

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Table 1. Estimates of the welfare loss due to climate change (as equivalent income loss in percent); estimates of the uncertainty are given in bracket as standard deviations or 95% confidence intervals.

Study	Warming	Impact	Worst-off region		Best-off region	
	(˚C)	(%GDP)	(%GDP)	(Name)	(%GDP)	(Name)
(Nordhaus, William D. 94b)	3.0	-1.3				
(Nordhaus 1994a)	3.0	-4.8 (-30.0 to 0.0)				
(Fankhauser, Samuel 95)	2.5	-1.4	-4.7	China	-0.7	Eastern Europe and the former Soviet Union
(Tol 1995)	2.5	-1.9	-8.7	Africa	-0.3	Eastern Europe and the former Soviet Union
(Nordhaus and Yang 1996)a	2.5	-1.7	-2.1	Developing countries	0.9	Former Soviet Union
(Plamberk and Hope 1996)a	2.5	-2.5 (-0.5 to –11.4)	-8.6 (-0.6 to -39.5)	Asia (w/o China)	0.0 (-0.2 to 1.5)	Eastern Europe and the former Soviet Union
(Mendelsohn et al. 2000a)a,b,c	2.5	0.0b 0.1b	-3.6b -0.5b	Africa	4.0b 1.7b	Eastern Europe and the former Soviet Union
(Nordhaus, William D. and Boyer, Joseph G. 00)	2.5	-1.5	-3.9	Africa	0.7	Russia
(Tol 2002a)	1.0	2.3 (1.0)	-4.1 (2.2)	Africa	3.7 (2.2)	Western Europe
(Maddison 2003)a,d,e	2.5	-0.1	-14.6	South America	2.5	Western Europe
(Rehdanz and Maddison 2005)a,c	1.0	-0.4	-23.5	Sub-Saharan Africa	12.9	South Asia
(Hope 2006)a,f	2.5	0.9 (-0.2 to 2.7)	-2.6 (-0.4 to 10.0)	Asia (w/o China)	0.3 (-2.5 to 0.5)	Eastern Europe and the former Soviet Union
(Nordhaus 2006)	2.5	-0.9 (0.1)				

[a] Note that the global results were aggregated by the current author.
[b] The top estimate is for the "experimental" model, the bottom estimate for the "cross-sectional" model.
[c] Note that Mendelsohn et al. only include market impacts.
[d] Note that the national results were aggregated to regions by the current author for reasons of comparability.
[e] Note that Maddison only considers market impacts on households.
[f] The numbers used by Hope are averages of previous estimates by (Fankhauser, Samuel 95) and (Tol 2002a); Stern *et al*. (2006) adopt the work of Hope.

Table 2. The social cost of carbon ($/tC); sample statistics and characteristics of the Fisher-Tippett distribution fitted to 311 published estimates, and to six alternative ways to split the sample.*

	All	PRTP			Review		Equity		Uncertainty		Age			Author			
		0%	1%	3%	Yes	No	Yes	No	Best	Mean	<1995	95-20	>2001	Hope	Nordhaus	Tol	Others
Mean	177	276	84	19	80	296	168	177	206	68	299	157	113	77	35	59	266
SD	293	258	93	18	109	442	200	316	332	93	522	227	153	119	51	75	403
Mode	49	126	48	10	26	70	65	44	55	23	43	48	42	20	9	25	67
P(SCC)<0	25%	10%	17%	11%	22%	24%	16%	27%	25%	22%	30%	23%	19%	26%	23%	14%	25%
33%	35	125	35	8	22	64	59	26	40	19	27	37	36	14	7	23	57
50%	116	212	71	15	57	192	117	112	135	49	175	106	81	53	21	46	177
67%	213	339	112	23	99	355	189	213	250	86	357	188	134	99	39	71	325
90%	487	646	204	44	206	814	478	489	573	177	916	429	273	219	105	139	734
95%	669	749	252	52	271	1165	614	690	777	233	1503	640	410	302	148	178	1002
99%	1602	966	359	68	504	1925	789	1684	1676	422	2139	957	679	504	200	286	1824
N	311	53	76	84	220	91	102	209	242	69	27	67	217	42	12	184	73

* PRTP = pure rate of time preference; review = peer-reviewed; equity = equity-weighted; uncertainty = best guess or mean value; age = year of publication; author = single or co-authors.

Year	Number	Title/Author(s) ESRI Authors/Co-authors *Italicised*
2011		
	376	The Economic Impact of Climate Change in the 20th Century *Richard S.J. Tol*
	375	Regional and Sectoral Estimates of the Social Cost of Carbon: An Application of FUND *David Anthoff*, Steven Rose, *Richard S.J. Tol* and Stephanie Waldhoff
	374	The Effect of REFIT on Irish Electricity Prices *Conor Devitt* and *Laura Malaguzzi Valeri*
	373	Economic Regulation: Recentralisation of Power or Improved Quality of Regulation? *Paul K. Gorecki*
	372	Goldilocks and the Three Electricity Prices: Are Irish Prices "Just Right"? *Conor Devitt, Seán Diffney, John Fitz Gerald,* *Laura Malaguzzi Valeri* and Aidan Tuohy
	371	The Climate Change Response Bill 2010: An Assessment *Paul K. Gorecki* and *Richard S.J. Tol*
	370	Shapley Values for Assessing Research Production and Impact of Schools and Scholars *Richard S.J. Tol*
	369	Determinants of Vegetarianism and Partial Vegetarianism in Ireland *Eimear Leahy, Seán Lyons, Richard S.J. Tol*
	368	Modified Ramsey Discounting for Climate Change *Richard S.J. Tol*
	367	A Cost-Benefit Analysis of the EU 20/20/2020 Package *Richard S.J. Tol*
	366	The Distributional Effects of Value Added Tax in Ireland *Eimear Leahy, Seán Lyons, Richard S.J. Tol*
2010		
	365	Explaining International Differences in Rates of Overeducation in Europe

	Maria A. Davia, Seamus McGuinness and *Philip, J. O'Connell*
364	The Research Output of Business Schools and Business Scholars in Ireland *Richard S.J. Tol*
363	The Effects of the Internationalisation of Firms on Innovation and Productivity *Iulia Siedschlag, Xiaoheng Zhang* and Brian Cahill
362	Too much of a good thing? Gender, 'Concerted cultivation' and unequal achievement in primary education *Selina McCoy, Delma Byrne, Joanne Banks*
361	Timing and Determinants of Local Residential Broadband Adoption: Evidence from Ireland *Seán Lyons*
360	Determinants of Vegetarianism and Partial Vegetarianism in the United Kingdom *Eimear Leahy, Seán Lyons* and *Richard S.J. Tol*
359	From Data to Policy Analysis: Tax-Benefit Modelling using SILC 2008 *Tim Callan, Claire Keane, John R. Walsh* and *Marguerita Lane*
358	Towards a Better and Sustainable Health Care System – Resource Allocation and Financing Issues for Ireland *Frances Ruane*
357	An Estimate of the Value of Lost Load for Ireland *Eimear Leahy* and *Richard S.J. Tol*
356	Public Policy Towards the Sale of State Assets in Troubled Times: Lessons from the Irish Experience *Paul K Gorecki, Sean Lyons* and *Richard S. J. Tol*
355	The Impact of Ireland's Recession on the Labour Market Outcomes of its Immigrants *Alan Barrett* and *Elish Kelly*
354	Research and Policy Making *Frances Ruane*
353	Market Regulation and Competition; Law in Conflict: A View from Ireland, Implications of the Panda Judgment Philip Andrews and *Paul K Gorecki*
352	Designing a property tax without property values: Analysis in the case of Ireland *Karen Mayor, Seán Lyons* and *Richard S.J. Tol*
351	Civil War, Climate Change and Development: A Scenario Study for Sub-Saharan Africa

	Conor Devitt and *Richard S.J. Tol*
350	Regulating Knowledge Monopolies: The Case of the IPCC *Richard S.J. Tol*
349	The Impact of Tax Reform on New Car Purchases in Ireland *Hugh Hennessy* and *Richard S.J. Tol*
348	Climate Policy under Fat-Tailed Risk: An Application of FUND *David Anthoff* and *Richard S.J. Tol*
347	Corporate Expenditure on Environmental Protection *Stefanie A. Haller* and *Liam Murphy*
346	Female Labour Supply and Divorce: New Evidence from Ireland Olivier Bargain, Libertad González, *Claire Keane* and Berkay Özcan
345	A Statistical Profiling Model of Long-Term Unemployment Risk in Ireland *Philip J. O'Connell, Seamus McGuinness, Elish Kelly*
344	The Economic Crisis, Public Sector Pay, and the Income Distribution *Tim Callan,* Brian Nolan (UCD) and *John Walsh*
343	Estimating the Impact of Access Conditions on Service Quality in Post *Gregory Swinand, Conor O'Toole* and *Seán Lyons*
342	The Impact of Climate Policy on Private Car Ownership in Ireland *Hugh Hennessy* and *Richard S.J. Tol*
341	National Determinants of Vegetarianism *Eimear Leahy, Seán Lyons* and *Richard S.J. Tol*
340	An Estimate of the Number of Vegetarians in the World *Eimear Leahy, Seán Lyons* and *Richard S.J. Tol*
339	International Migration in Ireland, 2009 *Philip J O'Connell* and *Corona Joyce*
338	The Euro Through the Looking-Glass: Perceived Inflation Following the 2002 Currency Changeover *Pete Lunn* and *David Duffy*
337	Returning to the Question of a Wage Premium for Returning Migrants *Alan Barrett and Jean Goggin*