

# The Economic Effects of Climate Change

Richard S. J. Tol

**G**reenhouse gas emissions are fundamental both to the world's energy system and to its food production. The production of CO<sub>2</sub>, the predominant gas implicated in climate change, is intrinsic to fossil fuel combustion; specifically, thermal energy is generated by breaking the chemical bonds in the carbohydrates oil, coal, and natural gas and oxidizing the components to CO<sub>2</sub> and H<sub>2</sub>O. One cannot have cheap energy without carbon dioxide emissions. Similarly, methane (CH<sub>4</sub>) emissions, an important greenhouse gas in its own right, are necessary to prevent the build-up of hydrogen in anaerobic digestion and decomposition. One cannot have beef, mutton, dairy, or rice without methane emissions.

Climate change is the mother of all externalities: larger, more complex, and more uncertain than any other environmental problem. The sources of greenhouse gas emissions are more diffuse than any other environmental problem. Every company, every farm, every household emits some greenhouse gases. The effects are similarly pervasive. Weather affects agriculture, energy use, health, and many aspects of nature—which in turn affects everything and everyone. The causes and consequences of climate change are very diverse, and those in low-income countries who contribute least to climate change are most vulnerable to its effects. Climate change is also a long-term problem. Some greenhouse gases have an atmospheric life-time measured in tens of thousands of years. The quantities of emissions involved are enormous. In 2000, carbon dioxide emissions alone (and excluding land use change) were 24 billion metric tons of carbon dioxide (tCO<sub>2</sub>).

■ *Richard S. J. Tol is Research Professor, Economic and Social Research Institute, Dublin, Ireland; and Professor of the Economics of Climate Change at the Institute for Environmental Studies and the Department of Spatial Economics, both at Vrije Universiteit, Amsterdam. His e-mail address is <richard.tol@esri.ie>.*

If all emissions were priced at the January 2009 price of €15/tCO<sub>2</sub>, that applied in the Emissions Trading System of the European Union, carbon dioxide would be worth 1.5 percent of world income. Finally, the uncertainties about climate change are vast—indeed, so vast that the standard tools of decision making under uncertainty and learning may not be applicable.<sup>1</sup>

In this essay, I begin with a review of the estimates of the total economic effects of climate change. I then focus on marginal cost estimates, which are especially important for economists thinking about policy design. I will also discuss many of the large gaps in current research on this topic. After the last two decades or so of study, I am reasonably confident that we know the scope of the research agenda in this area. For some economic effects of climate change, we have reasonable estimates; for others, we know at least an order of magnitude. We also have a clear idea of the sensitivities of these estimates to particular assumptions, even though in some cases we do not really know what to assume. Research in this area has reached the point that we can now identify our areas of ignorance; I believe that there are no more unknown unknowns, or at least no sizeable ones. But my belief here may suffer from overconfidence. In a survey article I co-authored more than a decade ago on the social costs of climate change, we suggested that all aspects of the problem were roughly known, and that research would be complete within a few years (Pearce et al., 1996). This view turned out to be so overoptimistic as to be entirely mistaken.

## **Estimates of the Total Economic Effect of Climate Change**

### **Methodologies**

The first studies of the welfare effects of climate change were done for the United States by Cline (1992), Nordhaus (1991), and Titus (1992; see also Smith, 1996). Although Nordhaus (1991; see also Ayres and Walter, 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 effects of climate change goes to Fankhauser (1994, 1995). Table 1 lists that study and a dozen other studies of the worldwide effects of climate change that have followed. The studies can be roughly divided into two groups: Nordhaus and Mendelsohn are colleagues and collaborators at Yale University; at University College of London, Fankhauser, Maddison, and I all worked with David Pearce and one another, while Rehdanz was a student of Maddison and mine.

Any study of the economic effects 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

<sup>1</sup> As one example, climate change affects human mortality and migration. The size of the population is therefore endogenous to the decision on emission abatement. See Blackorby and Donaldson (1984).

Table 1

**Estimates of the Welfare Impact of Climate Change**  
*(expressed as an equivalent income gain or loss in percent GDP)*

Study	Warming (°C)	Impact (% of GDP)	Worst-off region		Best-off region	
			(% of GDP)	(Name)	(% of GDP)	(Name)
Nordhaus (1994a)	3.0	−1.3				
Nordhaus (1994b)	3.0	−4.8 (−30.0 to 0.0)				
Fankhauser (1995)	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) <sup>a</sup>	2.5	−1.7	−2.1	Developing countries	0.9	Former Soviet Union
Plambeck and Hope (1996) <sup>a</sup>	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, Schlesinger, and Williams (2000) <sup>a,b,c</sup>	2.5	0.0 <sup>b</sup> 0.1 <sup>b</sup>	−3.6 <sup>b</sup> −0.5 <sup>b</sup>	Africa	4.0 <sup>b</sup> 1.7 <sup>b</sup>	Eastern Europe and the former Soviet Union
Nordhaus and Boyer (2000)	2.5	−1.5	−3.9	Africa	0.7	Russia
Tol (2002)	1.0	2.3 (1.0)	−4.1 (2.2)	Africa	3.7 (2.2)	Western Europe
Maddison (2003) <sup>a,d,e</sup>	2.5	−0.1	−14.6	South America	2.5	Western Europe
Rehdanz and Maddison (2005) <sup>a,c</sup>	1.0	−0.4	−23.5	Sub-Saharan Africa	12.9	South Asia
Hope (2006) <sup>a,f</sup>	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)				

*Note:* Where available, estimates of the uncertainty are given in parentheses, either as standard deviations or as 95 percent confidence intervals.

<sup>a</sup> The global results were aggregated by the current author.

<sup>b</sup> The top estimate is for the “experimental” model, the bottom estimate for the “cross-sectional” model.

<sup>c</sup> Mendelsohn et al. only include market impacts.

<sup>d</sup> The national results were aggregated to regions by the current author for reasons of comparability.

<sup>e</sup> Maddison only considers market impacts on households.

<sup>f</sup> The numbers used by Hope (2006) are averages of previous estimates by Fankhauser and Tol; Stern et al. (2006) adopt the work of Hope (2006).

storminess. The studies must then translate from climate change to economic consequences. A range of methodological approaches is possible here.

Nordhaus (1994b) interviewed a limited number of experts.

The studies by Fankhauser (1994, 1995), Nordhaus (1994a), and me (Tol, 1995, 2002a, b) 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 agricultural products, an example of a traded good or service, agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value the change in output. As another example, the effect of sea level rise is composed of additional coastal protection and land lost, estimates of which can be found in the engineering literature; the economic input in this case then includes not only the cost of dike-building and the value of land, but also the decisions about which properties to protect. For nonmarket goods and services, such as health, 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 monetization of nonmarket climate change effects 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 contexts other than climate change.

An alternative approach, exemplified in Mendelsohn’s work (Mendelsohn, Morrison, Schlesinger, and Andronova, 2000; Mendelsohn, Schlesinger, and Williams, 2000) 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 effect of climate change. Mendelsohn’s estimates are done per sector for selected countries, extrapolated to other countries, and then added up, but physical modeling is avoided. Studies by Nordhaus (2006) and Maddison (2003) use versions of the statistical approach as well. However, Nordhaus uses empirical estimates of the *aggregate* climate impact on income across the world (per grid cell), while Maddison (2003) 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 and easily interpreted. 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 in response to both market and nonmarket 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, modeled. 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 effects of sea level rise and carbon dioxide fertilization, do not have much spatial variation.

### **Findings and Implications**

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. The assumed warming typically presumes a doubling of concentrations of greenhouse gases in the atmosphere. It is reasonable to think of these as the temperature increase in the second half of the twenty-first century. However, the studies in Table 1 are comparative static—and thus they effectively 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 effect on welfare at that future time, usually expressed as a percentage of income. For instance, Nordhaus (1994a) estimates that the effect of 3°C global warming is as bad as losing 1.3 percent 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 do not report any estimate of the uncertainty. The rest of Table 1 illustrates differential effects around the world. The third column shows the percentage change 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 climate change—and in most cases would even benefit from a warmer climate—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. This kind of loss of output can look large or small, depending on context. From one perspective, it's 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. On the other hand, 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. Balancing these factors, cost-benefit analyses of climate change typically recommend only limited green-

house gas emission reduction—for instance, Nordhaus (1993) argues that the optimal rate of emission reduction is 10–15 percent (relative to the scenario without climate policy) over the course of the twenty-first century. For comparison, the European Union calls for 20–30 percent emission reduction (relative to 2005) by 2020.

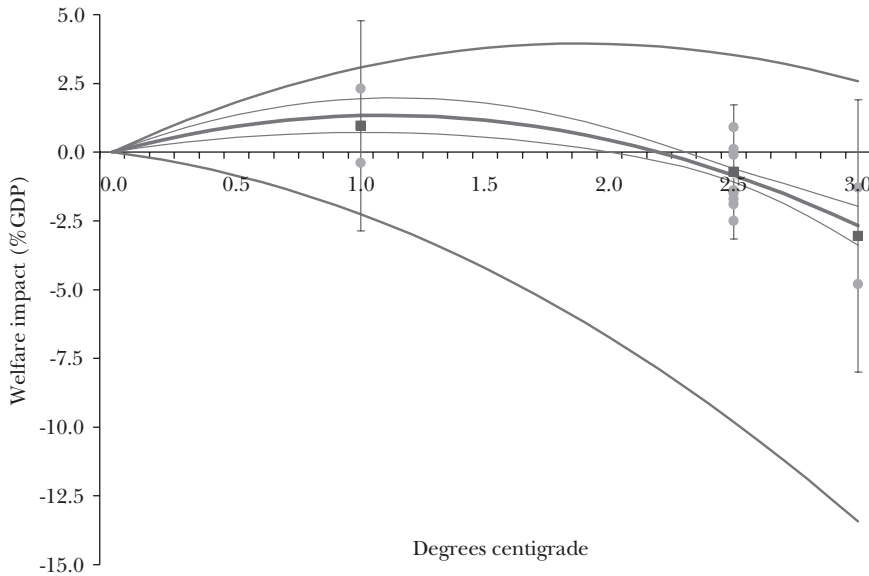
A second finding is that some estimates, by Hope (2006), Mendelsohn, Morrison, Schlesinger, and Andronov (2000), Mendelsohn, Schlesinger, and Williams (2000), and myself (Tol, 2002b), point to initial *benefits* of a modest increase in temperature, followed by losses as temperatures increase further. Figure 1 illustrates the pattern. There are no estimates for a warming above 3°C, although climate change may well go beyond that (as discussed below). All studies published after 1995 have regions with net gains and net losses due to global warming, while earlier studies only find net losses.

The horizontal axis of Figure 1 shows the increase in average global temperature. The vertical index shows the central estimate of welfare impact. 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, Morrison, Schlesinger, and Andronova, 2000; Mendelsohn, Schlesinger, and Williams, 2000; Nordhaus and Boyer, 2000; Tol, 2002b; also, compare Figure 19-4 in Smith et al., 2001).

The initial benefits arise partly because more carbon dioxide in the atmosphere reduces “water stress” in plants and may make them grow faster (Long, Ainsworth, Leakey, Noesberger, and Ort, 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—at least over the interval of small increases in global temperatures—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 1.1°C warming (with a standard deviation of 0.7°C). 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—which is to say, at just about the time that any medium-run economic benefits of climate change begin to decline (Hitz and Smith, 2004; Tol, 2002b; Tol, Fankhauser, Richels, and Smith, 2000). In short, even though total economic

Figure 1

**Fourteen Estimates of the Global Economic Impact of Climate Change**

Note: Figure 1 shows 14 estimates of the global economic impact of climate change, expressed as the welfare-equivalent income gain or loss, as a function of the increase in global mean temperature relative to today. The circular dots represent the estimates (from Table 1). The squares are the sample means (for the specific global warming), and the lines are the sample means plus or minus twice the sample standard deviation. The central heavier 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 thin inner two lines are the 95 percent confidence interval for the central line re-estimated with one observation dropped. The thick outer two lines are the 95 percent confidence interval, where the standard deviation is the least squares fit to the five reported standard deviations or half-confidence intervals (again, compare with Table 1):  $S_{\text{optimistic}} = 0.87(0.28)T$ ;  $R^2 = 0.70$ ,  $S_{\text{pessimistic}} = 1.79(0.87)T$ ;  $R^2 = 0.51$ , where  $S$  is the standard deviation.

effects of 1–2°C warming may be positive, incremental impacts beyond that level are likely to be negative. Moreover, if one looks further into the future, the incremental effects look even more 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 (see also Yohe and Schlesinger, 2002). Indeed, impact estimates for sub-Saharan Africa go up to a welfare loss equivalent to a quarter of income (as shown in Table 1). The estimates for low-income countries 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, Chiabai, and Meuhlenbachs,



2006; Smit and Wandel, 2006; Tol, 2008b; Tol and Yohe, 2007b; Yohe and Tol, 2002).

The emissions of greenhouse gases are predominantly from high-income countries while the negative effects of climate change are predominantly in low-income countries. This pattern holds two policy implications: First, any justification of stringent abatement for greenhouse gases is at least in part an appeal to consider the plight of citizens of low-income countries around the world and the effects imposed on them by the citizens of high-income countries (Schelling, 2000). Second, if pre-existing poverty is one of the main causes for vulnerability to climate change, one may wonder whether stimulating economic growth or emission abatement is the better way to reduce the effects of climate change. Indeed, in Tol and Dowlatabadi (2001) and Tol and Yohe (2006), my coauthors and I argue that the economic growth foregone by stringent abatement of greenhouse gases would more than offset the avoided effects of climate change, at least in the case of malaria. Similarly, in Tol (2005), I show that development is a cheaper way of reducing climate-change-induced malaria than is emission reduction. Moreover, high-income countries may find it easier and cheaper to compensate poorer countries for the climate change damages caused, rather than to pay for reducing their own greenhouse gas emissions. Such compensation could be explicit, but would more likely take the shape of technical and financial assistance with adaptation (Paavola and Adger, 2006).

Although research is scarce—O'Brien, Sygna, Haugen (2004) being one of the few exceptions—climate change effects would not be homogeneous within countries; certainly, particular economic sectors (like agriculture), regions (like coastal zones), and age groups (like the elderly) are more heavily affected than others.

Fourth, estimates of the economic effects of greenhouse gas emissions have become less pessimistic over time. For the studies listed here, the estimates become less negative 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 effects of climate change, whereas later studies considered the balance of positives and negatives. In addition, earlier studies tended to ignore adaptation. More recent studies—triggered by Mendelsohn, Nordhaus, and Shaw (1994)—include some provision for agents to alter their behavior 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 right-skewed. For example, consider only the studies that are based on a benchmark warming of 2.5°C. 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 for the 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 hints at a rough degree of 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 economic growth.

Figure 1 has three alternative estimates of the uncertainty around the central estimates. First, it shows the sample statistics. However, these 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 each time. 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 not significant) 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 short, 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.

### Improving Future Estimates

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.<sup>2</sup>

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 effect of climate change on agriculture by Mendelsohn, Nordhaus, and Shaw (1994) were in stark contrast to earlier results like those of Parry (1990), which suggests that this issue may be important. Realistic modeling of adaptation is problematic, and studies typically either assume no adaptation or perfect adaptation. Many effects are unquantified, and some of these effects may be large (as discussed below). The uncertainties of the estimates are largely unknown. These problems are gradually being addressed, but progress is slow. The list of warnings given here is similar to those in papers I've written with Fankhauser (Fankhauser and Tol, 1996, 1997).

A deeper conceptual issue arises with putting value on environmental services. Empirical studies have shown that the willingness to pay for improved environmental services may be substantially lower than the willingness to accept compensation for diminished environmental services (for example, Horowitz and McConnell, 2002). The difference between willingness to pay and willingness to accept compensation goes beyond income effects and may even hint at loss aversion and agency effects, particularly when involving issues of 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

<sup>2</sup> General equilibrium studies of the effect of climate change on agriculture have a long history (Kane, Reilly, and Tobey, 1992; Darwin, 2004). These papers show that markets matter, and may even reverse the sign of the initial impact estimate (Yates and Strzepek, 1998). In Bosello, Roson, and Tol (2007) and Darwin and Tol (2001), my coauthors and I 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, in Bosello, Rosen, and Tol (2006), we show that the direct costs are biased towards zero for health, that is, direct benefits and costs are smaller in absolute value than benefits and costs estimated by a general equilibrium model. This is because countries that would see their labor productivity fall (rise) because of climate change would also lose (gain) competitiveness, so that trade effects amplify the initial impact. In Berrittella, Bigano, Roson, and Tol (2006), my coauthors and I also emphasize the redistribution of impacts on tourism through markets.

pay as the basis for valuation of environmental services, as recommended by Arrow, Solow, Portney, Leamer, Radner, and Schuman (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 question is a different one, and the answer would be different if future generations are loss averse or distinguish between self-imposed and other-imposed risks. The current generation does, and the willingness to accept compensation tends to be higher than the willingness to pay. Consequently, the marginal avoided compensation would be larger than the marginal benefit, so the tax on greenhouse gas emission would be higher.

### **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 includes 13 studies and 14 estimates; in contrast, in Tol (2008a), I report 47 studies with 211 estimates of the marginal damage cost, and more have been published since then, including Hope (2008a, b), Nordhaus (2008), and Stern and Taylor (2007). However, it is not always recognized that marginal damage cost estimates are derived from total cost estimates. Some of the total cost estimates—including Maddison (2003), Mendelsohn, Morrison, Schlesinger, and Andronova (2000), Mendelson, Schlesinger, and Williams (2000), Nordhaus (2006), and Rehdanz and Maddison (2005)—have yet to be used for marginal cost estimation. Therefore, the 200-plus estimates of the social cost of carbon are based on nine estimates of the total effect 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 200 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 are 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<sup>3</sup>; some more recent studies have also analyzed variants of hyperbolic discounting, where the rate of discount falls over time.

Moreover, 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<sub>2</sub> 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, Nordhaus's (1991) estimate of the total welfare loss of a 3.0°C warming is 1.3 percent of GDP. To derive a marginal damage cost estimate from this, you would need to assume when, in the future, warming of 3.0°C would occur and whether damages are linear or quadratic or some other function of temperature (and precipitation and other factors). Then, the future stream of incremental damages due to today's emissions would need to be discounted back to today's value.

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 monetized 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, Hepburn, and Tol, 2009; Fankhauser, Tol, and Pearce, 1997).

Table 2 shows some characteristics of a meta-analysis of the published estimates of the social cost of carbon. The first set of columns show the sample statistics of the 232 published estimates. One key issue in attempting to summarize this work is that 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, forthcoming). Because there are many estimates of the social cost of carbon, a

<sup>3</sup> 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 (Ramsey) 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. All climate policy analyses that I am aware of use the same numerical value for risk aversion, consumption smoothing over time, domestic inequity aversion, and international aversion, although these four issues are conceptually distinct (as discussed in Saelen, Atkinson, Dietz, Helgeson, and Hepburn, 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.

Table 2  
**The Social Cost of Carbon**  
*(measured in \$/tC)*

	<i>Sample (unweighted)</i>				<i>Fitted distribution (weighted)</i>			
	<i>All</i>	<i>Pure rate of time preference</i>			<i>All</i>	<i>Pure rate of time preference</i>		
		<i>0%</i>	<i>1%</i>	<i>3%</i>		<i>0%</i>	<i>1%</i>	<i>3%</i>
Mean	105	232	85	18	151	147	120	50
Standard Deviation	243	434	142	20	271	155	148	61
Mode	13	—	—	—	41	81	49	25
33 <sup>rd</sup> percentile	16	58	24	8	38	67	45	20
Median	29	85	46	14	87	116	91	36
67 <sup>th</sup> percentile	67	170	69	21	148	173	142	55
90 <sup>th</sup> percentile	243	500	145	40	345	339	272	112
95 <sup>th</sup> percentile	360	590	268	45	536	487	410	205
99 <sup>th</sup> percentile	1500	—	—	—	1687	667	675	270
<i>N</i>	232	38	50	66	—	—	—	—

*Note:* Numbers in the table show the social cost of carbon measured in 1995 dollars per metric ton of carbon (\$/tC). Estimates are based on sample statistics and characteristics of the Fisher–Tippett distribution fitted to 232 published estimates and to three subsets of these estimates based on the pure rate of time preference.

probability density function can be constructed in a reasonably objective way. (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 I used in Tol (2008a).<sup>4</sup> The results are shown in the second set of columns in Table 2, labeled “Fitted distribution.”

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 \$105 per metric ton of carbon, but the modal estimate is only \$13/tC. Of course, this divergence suggests that the mean estimate is driven by some very large estimates—and indeed, the estimated social cost at the 95<sup>th</sup> percentile is \$360/tC and the estimate at the 99<sup>th</sup> percentile is \$1500/tC. The fitted distribution suggests that the

<sup>4</sup> 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, forthcoming). 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. See <http://www.fnu.zmaw.de/Social-cost-of-carbon-meta-analy.6308.0.html>.

sample statistics underestimate the marginal costs: the mode is \$41/tC; the mean, \$151/tC; and the 99<sup>th</sup> percentile, \$1687/tC.

This large divergence is partly explained by the use of different pure rates of time preference in these studies. For the sample and fitted distribution statistics (first and second set of columns in Table 2), the studies have been divided up into three subsamples based on the pure rate of time preference used in the study (0, 1, or 3 percent). 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 \$18/tC, while it is \$232/tC for studies that choose a 0 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. For the fitted distribution, the means are roughly double the modes—showing that the means are being pulled higher by some studies with very high estimated social costs.<sup>5</sup> Table 2 shows that the estimates for the whole sample are dominated by the estimates based on lower discount rates.

The sample and distribution characteristics of Table 2 also allow us to identify outliers. On the low side, my results (Tol, 2005) stand out with a social cost of carbon of  $-\$6.6/\text{tC}$  for a 3 percent pure rate of time preference and  $\$19.9/\text{tC}$  for a 0 percent rate. The reason is that my model was the first of those used for marginal cost estimation that showed initial benefits from climate change. In my later work, the early benefits are less pronounced. On the high side, the results of Ceronsky, Anthoff, Hepburn, and Tol (2006) stand out, with a social cost estimate of  $\$2400/\text{tC}$  for a 0 percent pure rate of time preference and  $\$120/\text{tC}$  for a 3 percent rate. The reason is that Ceronsky et al. consider extreme scenarios only—while they acknowledge that such scenarios are unlikely, they do not specify a probability. At a 1 percent pure rate of time preference, the  $\$815/\text{tC}$  estimate of Hope (2008a) stands out. Again, this is the result of a sensitivity analysis in which Hope sets risk aversion to zero so that the consumption discount rate equals 1 percent as well.

Although Table 2 reveals a large estimated uncertainty about the social cost of carbon, the actual uncertainty may well be 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 below 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

<sup>5</sup> Some readers may wonder why the estimates with a discount rate of 0 percent don't look all that substantially higher than the estimates with a discount rate of 1 percent. 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 reserves are finite and the economy would eventually equilibrate with the new climate, but the effect of the 0 percent discount rate would be more substantial. For the record, there is even one estimate (Hohmeyer and Gartner, 1992) based on a 0 percent consumption discount rate (as discussed in Davidson, 2006) and thus a *negative* pure rate of time preference.

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, a carbon tax in the range of \$50–\$100 per metric ton 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 remain very expensive (Schaefer and Jacoby, 2005, 2006). Substantial reduction of carbon emissions thus requires a carbon tax of at least \$50/tC—which is just barely justifiable at the mean estimate for a pure rate of time preference of 3 percent.

## Missing Effects

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, and human health. Obviously, this list is incomplete. Even within each category, the assessment is incomplete. I cannot offer quantitative estimates of these missing effects, but a qualitative and speculative assessment of their relative importance follows. For more detail, see Tol (2008c).

Many of the omissions seem likely to be relatively small in the context of 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, Buzas, and Clement, 1997). Redesigning urban water management systems, be it for more or less water, would be costly (Ashley, Balmford, Saul, and Blanksby, 2005), as would implementing safeguards against increased uncertainty about future circumstances. Extratropical storms may increase, leading to greater damage and higher building standards (Dorland, Tol, and Palutikof, 1999). Tropical storms do more damage, but it is not known how climate change would alter the frequency, intensity, and spread of tropical storms (McDonald, Bleaken, Cresswell, Pope, and Senior, 2005). Ocean acidification may harm fisheries (Kikkawa, Kita, and Ishimatsu, 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 harbors, 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, Falkingham, Melling, and de Abreu, 2004). Warmer weather would reduce expenditures on clothing and food, and traffic disruptions due to snow and ice (Carmicheal, Gallus, Temeyer, and Bryden, 2004).



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

These relatively 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 change could 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 and Spouge, 2002), which would lead to a 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 Huang, 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. In Nicholls, Tol, and Vafeidis (2008), my coauthors and I find that the effects of sea level rise would increase ten-fold should the West Antarctic Ice Sheet collapse. But the work of Olsthoorn, van der Werff, Bouwer, and Huitema (2008) suggests that this may be too optimistic; that we may have overestimated the speed with which coastal protection can be built up. In Link and Tol (2004), my coauthor and I estimate the effects of a shutdown of the thermohaline circulation. We 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<sub>2</sub>; 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 (as suggested by 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, or 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 effects grow faster than the discount rate—because of the large uncertainty, this outcome 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 these issues. 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, Boyle, and Brown, 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 the 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 (Gallup, Sachs, and Mellinger, 1999; Acemoglu, Johnson, and Robinson, 2001; Masters and McMillan, 2001; van Kooten, 2004; Nordhaus, 2006), although others would argue that institutions are more important than geography (Acemoglu, Johnson, and Robinson, 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. In Fankhauser and Tol (2005), my coauthor and I argue that only very extreme parameter choices would imply such a scenario. In contrast, Dell, Jones, and Olken (2008) find that climate change would slow the *annual* growth rate of poor countries by 0.6 to 2.9 percentage points. Accumulated over a century, this effect would dominate all earlier estimates of the economic effects of climate change. However, Dell et al. 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 diarrhea, in a way that affects long-term economic growth (for example, via a mechanism as in Galor and Weil, 1999); or in which climate-change-induced resource scarcity intensifies violent conflict (Zhang, Zhang, Lee, and He, 2007; Tol and Wagner, 2008) and affect long-term growth rates through that mechanism (Butkiewicz and Yanikkaya, 2005). These potential channels have not been modeled 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 labor productivity has never featured on any list of missing effects, but Kjellstrom, Kovats, Lloyd, Holt, and Tol (2008) show that it may well be substantial.

The missing effects further emphasize that climate change may spring nasty surprises. Such risks justify greenhouse gas emission reduction beyond that recommended by a cost–benefit analysis under quantified risk. The size of the appropriate “uncertainty premium” is in some sense 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). More recent research has dispelled these fears.

## Conclusion

The quantity and intensity of the research effort on the economic effects of climate change seems incommensurate with the perceived size of the climate problem, the expected costs of the solution, and the size of the existing research gaps. Politicians are proposing to spend hundreds of billions of dollars on greenhouse gas emission reduction, and at present, economists cannot say with confidence whether this investment is too much or too little.

The best available knowledge—which is not very good—is given in Table 2. A government that uses the same 3 percent discount rate for climate change as for other decisions should levy a carbon tax of \$25 per metric ton of carbon (modal value) to \$50/tC (mean value). A higher tax can be justified by an appeal to the high level of risk, especially of very negative outcomes, not captured in the standard estimates (Weitzman, forthcoming). The price of carbon dioxide emission permits in the European Union was \$78/tC in January 2009. The United States has no federal policy specifically to reduce carbon emissions, although many utilities apparently factor in the likelihood of a carbon tax of \$15/tC in their investment decisions (Richels, personal communication). This pattern suggests that the European Union may be placing too high a price on carbon emissions, while the United States is placing too low a price on such emissions. Outside the high-income countries of the world, essentially no climate policy exists—although these countries are most vulnerable to climate change, and some of them like China and India are major emitters of carbon. Many of these countries subsidize fossil fuel use, rather than taxing it.

There is a strong case for near-term action on climate change, although prudence may dictate phasing in a higher cost of carbon over time, both to ease the transition and to give analysts the ongoing ability to evaluate costs, benefits, and policy mechanisms.

■ *Discussions with David Anthoff, Sam Fankhauser, Bill Nordhaus, David Maddison, Robert Mendelsohn, Steve Pacala, Katrin Rehdanz, Rich Richels, Joel Smith, Rob Socolow, John Weyant, Bob Williams, and Gary Yohe have shaped my thinking on the issues discussed in this paper. David Pearce stands out for his early encouragement and for emphasizing intellectual honesty over political correctness. Rob Stavins also deserves special mention. James Hines, Gilbert Metcalf, Andrei Shleifer, Jeremy Stein, and particularly Timothy Taylor had excellent comments on an earlier version of the paper. Financial support by the ESRI Energy Policy Research Centre and CEC FP7 Climate Cost project is gratefully acknowledged.*

## References

- Acemoglu, Daron, Simon Johnson, and James A. Robinson.** 2001. "The Colonial Origins of Comparative Development: An Empirical Investigation." *American Economic Review*, 91(4): 1369–1401.
- Acemoglu, Daron, Simon Johnson, and James A. Robinson.** 2002. "Reversal of Fortune: Geography and Institutions in the Making of the Modern World Income Distribution." *Quarterly Journal of Economics*, 117(4): 1231–94.
- Adger, W. Neil.** 2006. "Vulnerability." *Global Environmental Change*, 16(3): 268–81.
- Alberini, Anna, Aline Chiabai, and Lucija Muehlenbachs.** 2006. "Using Expert Judgement to Assess Adaptive Capacity to Climate Change: Evidence from a Conjoint Choice Survey." *Global Environmental Change*, 16(2): 123–44.
- Anthoff, David, Cameron J. Hepburn, Richard S. J. Tol.** 2009. "Equity Weighting and the Marginal Damage Costs of Climate Change." *Ecological Economics*, 68(3): 836–49.
- Arrow, Kenneth J., Robert M. Solow, Paul R. Portney, Edward E. Leamer, Roy Radner, and Howard Schuman.** 1993. "Report of the NOAA Panel on Contingent Valuation." *Federal Register*, 58(10): 4016–64.
- Ashley, Richard M., David J. Balmforth, Adrian J. Saul, and John D. Blanksby.** 2005. "Flooding in the Future—Predicting Climate Change, Risks and Responses in Urban Areas." *Water Science and Technology*, 52(5): 265–73.
- Ayres, Robert U., and Joerg Walter.** 1991. "The Greenhouse Effect: Damages, Costs and Abatement." *Environmental and Resource Economics*, 1(3): 237–70.
- Berrittella, Maria, Andrea Bigano, Roberto Roson, and Richard S. J. Tol.** 2006. "A General Equilibrium Analysis of Climate Change Impacts on Tourism." *Tourism Management*, 27(5): 913–24.
- Blackorby, Charles, and David Donaldson.** 1984. "Social Criteria for Evaluating Population Change." *Journal of Public Economics*, 25(1–2): 13–33.
- Bosello, Francesco, Roberto Roson, and Richard S. J. Tol.** 2006. "Economy-wide Estimates of the Implications of Climate Change: Human Health." *Ecological Economics*, 58(3): 579–91.
- Bosello, Francesco, Roberto Roson, and Richard S. J. Tol.** 2007. "Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise." *Environmental and Resource Economics*, 37(3): 549–71.
- Breslow, Paul B., and David J. Sailor.** 2002. "Vulnerability of Wind Power Resources to Climate Change in the Continental United States." *Renewable Energy*, 27(4): 585–98.
- Brouwer, Roy, and Frank A. Spaninks.** 1999. "The Validity of Environmental Benefits Transfer: Further Empirical Testing." *Environmental and Resource Economics*, 14(1): 95–117.
- Butkiewicz, James L., and Halit Yanikkaya.** 2005. "The Impact of Sociopolitical Instability on Economic Growth: Analysis and Implications." *Journal of Policy Modeling*, 27(5): 629–45.
- Carmichael, Craig G., William A. Gallus, Jr., Bradley R. Temeyer, Mark K. Bryden.** 2004. "A Winter Weather Index for Estimating Winter Roadway Maintenance Costs in the Midwest." *Journal of Applied Meteorology*, 43(11): 1783–90.
- Ceronsky, Megan, David Anthoff, Cameron J. Hepburn, and Richard S. J. Tol.** 2006. *Checking*

*the Price Tag on Catastrophe: The Social Cost of Carbon under Non-linear Climate Response*. Working Paper FNU-87, Sustainability and Global Change research unit, Hamburg University; and Centre for Marine and Atmospheric Science.

**Champ, Patricia A., Kevin J. Boyle, and Thomas C. Brown, eds.** 2003. *A Primer on Non-market Valuation*. Dordrecht/Boston/London: Kluwer Academic Publishers.

**Cline, William R.** 1992. *The Economics of Global Warming*. Washington, DC: Institute for International Economics.

**Darwin, Roy F.** 2004. "Effects of Greenhouse Gas Emissions on World Agriculture, Food Consumption, and Economic Welfare." *Climatic Change*, 66(1-2): 191-238.

**Darwin, Roy F., and Richard S. J. Tol.** 2001. "Estimates of the Economic Effects of Sea Level Rise." *Environmental and Resource Economics*, 19(2): 113-29.

**Davidson, Marc D.** 2006. "A Social Discount Rate for Climate Damage to Future Generations based on Regulatory Law." *Climatic Change*, 76(1-2): 55-72.

**Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken.** 2008. *Climate Change and Economic Growth: Evidence from the Last Half Century*. National Bureau of Economic Research Working Paper 14132.

**Dorland, Cornelis, Richard S. J. Tol, and Jean P. Palutikof.** 1999. "Vulnerability of the Netherlands and Northwest Europe to Storm Damage under Climate Change." *Climatic Change*, 43(3): 513-35.

**Easterly, William, and Ross Levine.** 2003. "Tropics, Germs, and Crops: How Endowments Influence Economic Development." *Journal of Monetary Economics*, 50(1): 3-39.

**Fankhauser, Samuel.** 1994. "The Social Costs of Greenhouse Gas Emissions: An Expected Value Approach." *Energy Journal*, 15(2): 157-84.

**Fankhauser, Samuel.** 1995. *Valuing Climate Change—The Economics of the Greenhouse*. London: EarthScan.

**Fankhauser, Samuel, and Richard S. J. Tol.** 1996. "Climate Change Costs—Recent Advancements in the Economic Assessment." *Energy Policy*, 24(7): 665-73.

**Fankhauser, Samuel, and Richard S. J. Tol.** 1997. "The Social Costs of Climate Change: The IPCC Second Assessment Report and Beyond." *Mitigation and Adaptation Strategies for Global Change*, 1(4): 385-403.

**Fankhauser, Samuel, and Richard S. J. Tol.** 2005. "On Climate Change and Economic Growth." *Resource and Energy Economics*, 27(1): 1-17.

**Fankhauser, Samuel, Richard S. J. Tol, and David W. Pearce.** 1997. "The Aggregation of Climate Change Damages: A Welfare Theoretic Approach." *Environmental and Resource Economics*, 10(3): 249-66.

**Gallup, John L., Jeffrey D. Sachs, and Andrew D. Mellinger.** 1999. "Geography and Economic Development." *International Regional Science Review*, 22(2): 179-232.

**Galor, Oded, and David N. Weil.** 1999. "From Malthusian Stagnation to Modern Growth." *American Economic Review*, 89(2): 150-54.

**Gitay, Habiba, et al.** 2001. "Ecosystems and their Goods and Services." In *Climate Change 2001: Impacts, Adaptation and Vulnerability—Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. James J. McCarthy, Osvaldo F. Canziani, Neil A. Leary, David J. Dokken, Katherine S. White, 235-342. Cambridge: Cambridge University Press.

**Haines, Andrew, and Chris Fuchs.** 1991. "Potential Impacts on Health of Atmospheric Change." *Journal of Public Health Medicine*, 13(2): 69-80.

**Harvey, L. D. Danny, and Huang Zhen.** 1995. "Evaluation of the Potential Impact of Methane Clathrate Destabilization on Future Global Warming." *Journal of Geophysical Research*, 100(D2): 2905-26.

**Hitz, Samuel, and Joel B. Smith.** 2004. "Estimating Global Impacts from Climate Change." *Global Environmental Change*, 14(3): 201-18.

**Hohmeyer, Olav, and Michael Gaertner.** 1992. *The Costs of Climate Change—A Rough Estimate of Orders of Magnitude*. Fraunhofer-Institut für Systemtechnik und Innovationsforschung.

**Hope, Chris W.** 2006. "The Marginal Impact of CO<sub>2</sub> from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern." *Integrated Assessment Journal*, 6(1): 19-56.

**Hope, Chris W.** 2008a. "Discount Rates, Equity Weights and the Social Cost of Carbon." *Energy Economics*, 30(3): 1011-19.

**Hope, Chris W.** 2008b. "Optimal Carbon Emissions and the Social Cost of Carbon over Time under Uncertainty." *Integrated Assessment Journal*, 8(1): 107-122.

**Horowitz, John K., and Kenneth E. McConnell.** 2002. "A Review of WTA/WTP Studies." *Journal of Environmental Economics and Management*, 44(3): 426-47.

**Kane, Sally, John M. Reilly, and James Tobey.** 1992. "An Empirical Study of the Economic Effects of Climate Change on World Agriculture." *Climatic Change*, 21(1): 17-35.



- Kikkawa, Takashi, Jun Kita, Atsushi Ishimatsu.** 2004. "Comparison of the Lethal Effect of CO<sub>2</sub> and Acidification on Red Sea Bream (*Pagrus Major*) during the Early Developmental Stages." *Marine Pollution Bulletin*, 48(1-2): 108-110.
- Kjellstrom, Tord, R. Sari Kovats, Simon L. Lloyd, M. Thomas Holt, and Richard S. J. Tol.** 2008. *The Direct Impact of Climate Change on Regional Labour Productivity*. Economic and Social Research Institute Working Paper 260.
- Kundzewicz, Zbigniew W., Dariusz Graczyk, Thomas Maurer, Iwona Pinkswar, Maciej Radziejewski, Cecilia Svensson, and Malgorzata Szwed.** 2005. "Trend Detection in River Flow Series: 1. Annual Maximum Flow." *Hydrological Sciences Journal*, 50(5): 797-810.
- Link, P. Michael, and Richard S. J. Tol.** 2004. "Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of FUND." *Portuguese Economic Journal*, 3(2): 99-114.
- Long, Stephen P., Elizabeth A. Ainsworth, Andrew D. B. Leakey, Josef Noesberger, and Donald R. Ort.** 2006. "Food for Thought: Lower-than-Expected Crop Yield Stimulation with Rising CO<sub>2</sub> Concentrations." *Science*, 312(5811): 1918-21.
- Maddison, David J.** 2003. "The Amenity Value of the Climate: The Household Production Function Approach." *Resource and Energy Economics*, 25(2): 155-75.
- Marotzke, Jochen.** 2000. "Abrupt Climate Change and Thermohaline Circulation: Mechanisms and Predictability." *Proceedings of the National Academy of Science*, 97(4): 1347-50.
- Masters, William A., and Margaret S. McMillan.** 2001. "Climate and Scale in Economic Growth." *Journal of Economic Growth*, 6(3): 167-86.
- McDonald, Ruth E., Daniel G. Bleaken, Denise R. Cresswell, Victoria D. Pope, and Catherine A. Senior.** 2005. "Tropical Storms: Representation and Diagnosis in Climate Models and the Impacts of Climate Change." *Climate Dynamics*, 25(1): 19-36.
- Mendelsohn, Robert O., Wendy N. Morrison, Michael E. Schlesinger, and Natalia G. Andronova.** 2000. "Country-specific Market Impacts of Climate Change." *Climatic Change*, 45(3-4): 553-69.
- Mendelsohn, Robert O., William D. Nordhaus, and Daigee Shaw.** 1994. "The Impact of Climate on Agriculture: A Ricardian Analysis." *American Economic Review*, 84(4): 753-71.
- Mendelsohn, Robert O., Michael E. Schlesinger, and Lawrence J. Williams.** 2000. "Comparing Impacts across Climate Models." *Integrated Assessment*, 1(1): 37-48.
- Nicholls, Robert J., and Richard S. J. Tol.** 2006. "Impacts and Responses to Sea Level Rise: A Global Analysis of the SRES Scenarios over the Twenty-First Century." *Philosophical Transactions of the Royal Society A*, 364(1849): 1073-95.
- Nicholls, Robert J., Richard S. J. Tol, and Athanasios T. Vafeidis.** 2008. "Global Estimates of the Impact of a Collapse of the West Antarctic Ice Sheet: An Application of FUND." *Climatic Change*, 91(1-2): 171-91.
- Nordhaus, William D.** 1991. "To Slow or Not to Slow: The Economics of the Greenhouse Effect." *Economic Journal*, 101(444): 920-37.
- Nordhaus, William D.** 1993. "Rolling the 'DICE': An Optimal Transition Path for Controlling Greenhouse Gases." *Resource and Energy Economics*, 15(1): 27-50.
- Nordhaus, William D.** 1994a. *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: MIT Press.
- Nordhaus, William D.** 1994b. "Expert Opinion on Climate Change." *American Scientist*, 82(1): 45-51.
- Nordhaus, William D.** 2006. "Geography and Macroeconomics: New Data and New Findings." *Proceedings of the National Academy of Science*, 103(10): 3510-17.
- Nordhaus, William D.** 2008. *A Question of Balance—Weighing the Options on Global Warming Policies*. New Haven: Yale University Press.
- Nordhaus, William D., and Joseph G. Boyer.** 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.
- Nordhaus, William D., and Zili Yang.** 1996. "RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy." *American Economic Review*, 86(4): 741-65.
- O'Brien, Karen L., Linda Sygna, and Jan Erik Haugen.** 2004. "Vulnerable or Resilient? A Multi-scale Assessment of Climate Impacts and Vulnerability in Norway." *Climatic Change*, 64(1-2): 193-225.
- Olsthoorn, Alexander A., Peter E. van der Werff, Laurens M. Bouwer, and Dave Huitema.** 2008. "Neo-Atlantis: The Netherlands under a 5-m Sea Level Rise." *Climatic Change*, 91(1-2): 103-122.
- Paavola, Jouni, and W. Neil Adger.** 2006. "Fair Adaptation to Climate Change." *Ecological Economics*, 56(4): 594-609.
- Parry, Martin L.** 1990. *Climate Change and World Agriculture*. London: EarthScan.
- Pearce, David W., William R. Cline, Amrita N. Achanta, Samuel Fankhauser, Rajendra K. Pachauri, Richard S. J. Tol, and Pier Vellinga.**

1996. "The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control." In *Climate Change 1995: Economic and Social Dimensions—Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, ed. James P. Bruce, Hoesung Lee, Eric F. Haites, 179–224. Cambridge: Cambridge University Press.
- Pearce, David W., and Dominic Moran.** 1994. *The Economic Value of Biodiversity*. London: Earthscan.
- Plamberk, Erika L., and Chris W. Hope.** 1996. "PAGE95—An Updated Valuation of the Impacts of Global Warming." *Energy Policy*, 24(9): 783–93.
- Rehdanz, Katrin, and David J. Maddison.** 2005. "Climate and Happiness." *Ecological Economics*, 52(1): 111–25.
- Saelen, Haakon, Giles D. Atkinson, Simon Dietz, Jennifer Helgeson, and Cameron J. Hepburn.** 2008. *Risk, Inequality and Time in the Welfare Economics of Climate Change: Is the Workhorse Model Underspecified?* Department of Economics, Oxford University Discussion Paper 400.
- Schaefer, Andreas, and Henry D. Jacoby.** 2005. "Technology Detail in a Multisector CGE Model: Transport under Climate Policy." *Energy Economics*, 27(1): 1–24.
- Schaefer, Andreas, and Henry D. Jacoby.** 2006. "Vehicle Technology under CO<sub>2</sub> Constraint: A General Equilibrium Analysis." *Energy Policy*, 34(9): 975–85.
- Schelling, Thomas C.** 2000. "Intergenerational and International Discounting." *Risk Analysis*, 20(6): 833–37.
- Schneider, Stephen H., and Robert S. Chen.** 1980. "Carbon Dioxide Warming and Coastline Flooding: Physical Factors and Climatic Impact." *Annual Review of Energy*, vol. 5, pp. 107–140.
- Smit, Barry, and Johanna Wandel.** 2006. "Adaptation, Adaptive Capacity and Vulnerability." *Global Environmental Change*, 16(3): 282–92.
- Smith, Joel B.** 1996. "Standardized Estimates of Climate Change Damages for the United States." *Climatic Change*, 32(3): 313–26.
- Smith, Joel B. et al.** 2001. "Vulnerability to Climate Change and Reasons for Concern: A Synthesis." In *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, ed. James J. McCarthy, Osvaldo F. Canziani, Neil A. Leary, David J. Dokken, and Katherine S. White, 913–67. Cambridge, UK: Press Syndicate of the University of Cambridge.
- Stern, Nicholas H. et al.** 2006. *Stern Review: The Economics of Climate Change*. Cambridge: Cambridge University Press.
- Stern, Nicholas H., and Chris Taylor.** 2007. "Climate Change: Risks, Ethics and the Stern Review." *Science*, 317(5835): 203–4.
- Szolnoky, Csaba, Kalman Buzas, and Adrienne Clement.** 1997. "Impacts of the Climate Change on the Operation of a Freshwater Cooled Electric Power Plant." *Periodica Polytechnica: Civil Engineering*, 41(2): 71–94.
- Titus, James G.** 1992. "The Costs of Climate Change to the United States." In *Global Climate Change: Implications, Challenges and Mitigation Measures*, ed. Shyamal K. Majumdar, Lawrence S. Kalkstein, Brenton M. Yarnal, Edward W. Miller, and Luke M. Rosenfeld, 384–409. Easton: Pennsylvania Academy of Science.
- Tol, Richard S. J.** 1995. "The Damage Costs of Climate Change Toward More Comprehensive Calculations." *Environmental and Resource Economics*, 5(4): 353–74.
- Tol, Richard S. J.** 2002a. "Estimates of the Damage Costs of Climate Change—Part 1: Benchmark Estimates." *Environmental and Resource Economics*, 21(1): 47–73.
- Tol, Richard S. J.** 2002b. "Estimates of the Damage Costs of Climate Change—Part II: Dynamic Estimates." *Environmental and Resource Economics*, 21(2): 135–60.
- Tol, Richard S. J.** 2003. "Is the Uncertainty about Climate Change Too Large for Expected Cost–Benefit Analysis?" *Climatic Change*, 56(3): 265–89.
- Tol, Richard S. J.** 2005. "Emission Abatement versus Development as Strategies to Reduce Vulnerability to Climate Change: An Application of FUND." *Environment and Development Economics*, 10(5): 615–29.
- Tol, Richard S. J.** 2008a. "The Social Cost of Carbon: Trends, Outliers and Catastrophes." *Economics—the Open-Access, Open-Assessment E-Journal*, 2(25): 1–24.
- Tol, Richard S. J.** 2008b. "Climate, Development, and Malaria: An Application of FUND." *Climatic Change*, 88(1): 21–34.
- Tol, Richard S. J.** 2008c. "Why Worry About Climate Change? A Research Agenda." *Environmental Values*, 17(4): 437–70.
- Tol, Richard S. J., and Hadi Dowlatabadi.** 2001. "Vector-borne Diseases, Development and Climate Change." *Integrated Assessment*, 2(4): 173–81.
- Tol, Richard S. J., Samuel Fankhauser, Richard G. Richels, and Joel B. Smith.** 2000. "How Much Damage Will Climate Change Do?" *World Economics*, 1(4): 179–206.
- Tol, Richard S. J., and Sebastian Wagner.** 2008. *Climate Change and Violent Conflict in Europe over the Last Millennium*. Working Paper FNU-154, Sustainability and Global Change research



unit, Hamburg University; and Centre for Marine and Atmospheric Science.

**Tol, Richard S. J., and Gary W. Yohe.** 2006. "Of Dangerous Climate Change and Dangerous Emission Reduction." In *Avoiding Dangerous Climate Change*, ed. Hans-Joachim Schellnhuber, Wolfgang Cramer, Nebojsa Nakicenovic, Thomas M. L. Wigley, Gary W. Yohe, 291–98. Cambridge: Cambridge University Press.

**Tol, Richard S. J., and Gary W. Yohe.** 2007a. "Infinite Uncertainty, Forgotten Feedbacks, and Cost–Benefit Analysis of Climate Change." *Climatic Change*, 83(4): 429–42.

**Tol, Richard S. J., and Gary W. Yohe.** 2007b. "The Weakest Link Hypothesis for Adaptive Capacity: An Empirical Test." *Global Environmental Change*, 17(2): 218–27.

**van Kooten, G. Cornelis.** 2004. *Climate Change Economics—Why International Accords Fail*. Cheltenham, UK, and Northampton, MA: Edward Elgar.

**Vaughan, David G., and John R. Spouge.** 2002. "Risk Estimation of Collapse of the West Antarctic Sheet." *Climatic Change*, 52(1–2): 65–91.

**Weitzman, Martin L.** Forthcoming. "On Modelling and Interpreting the Economics of Catastrophic Climate Change." *Review of Economics and Statistics*.

**Weyant, John P., Francisco C. de la Chesnaye, and Geoffrey J. Blanford.** 2006. "Overview of EMF-21: Multigas Mitigation and Climate Policy." *Energy Journal*, (Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue): 1–32.

**Wilson, Katherina J., John Falkingham, Humfrey Melling, and Roger A. de Abreu.** 2004. "Shipping in the Canadian Arctic: Other Possible Climate Change Scenarios." *International Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. IEEE International*, vol. 3, pp. 1853–56.

**Yohe, Gary W., and Michael E. Schlesinger.** 2002. "The Economic Geography of the Impacts of Climate Change." *Journal of Economic Geography*, 2(3): 311–41.

**Yates, David N., and Kenneth M. Strzepek.** 1998. "An Assessment of Integrated Climate Change Impacts on the Agricultural Economy of Egypt." *Climatic Change*, 38(3): 261–87.

**Yohe, Gary W., and Richard S. J. Tol.** 2002. "Indicators for Social and Economic Coping Capacity—Moving Towards a Working Definition of Adaptive Capacity." *Global Environmental Change*, 12(1): 25–40.

**Zhang, David D., Jane Zhang, Harry F. Lee, and Yuan-Qing He.** 2007. "Climate Change and War Frequency in Eastern China over the Last Millennium." *Human Ecology*, 35(4): 403–414.

**This article has been cited by:**

1. Philip E. Graves. 2017. Global Climate Policy Will Have Net Benefits Larger Than Anyone Thinks (and Welfare Gains, Strangely, Are Likely To Be Much Larger Yet). *Ecological Economics* **136**, 73-76. [[CrossRef](#)]
2. Paul Cashin, Kamiar Mohaddes, Mehdi Raissi. 2017. Fair weather or foul? The macroeconomic effects of El Niño. *Journal of International Economics* **106**, 37-54. [[CrossRef](#)]
3. Kent Kovacs, Grant West, Ying Xu. 2017. The use of efficiency frontiers to evaluate the optimal land cover and irrigation practices for economic returns and ecosystem services. *Journal of Hydrology* **547**, 474-488. [[CrossRef](#)]
4. Luis Ignacio Rizzi, Cristobal De La Maza. 2017. The external costs of private versus public road transport in the Metropolitan Area of Santiago, Chile. *Transportation Research Part A: Policy and Practice* **98**, 123-140. [[CrossRef](#)]
5. Daiju Narita, Katrin Rehdanz. 2017. Economic impact of ocean acidification on shellfish production in Europe. *Journal of Environmental Planning and Management* **60**:3, 500-518. [[CrossRef](#)]
6. Hongbo Duan, Gupeng Zhang, Shouyang Wang, Ying Fan. 2017. Balancing China's climate damage risk against emission control costs. *Mitigation and Adaptation Strategies for Global Change* . [[CrossRef](#)]
7. Francisco Estrada, Richard S. J. Tol, Wouter J. W. Botzen. 2017. Global economic impacts of climate variability and change during the 20th century. *PLOS ONE* **12**:2, e0172201. [[CrossRef](#)]
8. William D. Nordhaus. 2017. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences* **114**:7, 1518-1523. [[CrossRef](#)]
9. Jeroen C. J. M. van den Bergh. 2017. A third option for climate policy within potential limits to growth. *Nature Climate Change* **7**:2, 107-112. [[CrossRef](#)]
10. Matteo Vizzarri, Lorenzo Sallustio, Davide Travaglini, Francesca Bottalico, Gherardo Chirici, Vittorio Garfi, Raffaele Laforteza, Donato La Mela Veca, Fabio Lombardi, Federico Maetzke, Marco Marchetti. 2017. The MIMOSE Approach to Support Sustainable Forest Management Planning at Regional Scale in Mediterranean Contexts. *Sustainability* **9**:2, 316. [[CrossRef](#)]
11. Gilbert Kollenbach. 2017. On the optimal accumulation of renewable energy generation capacity. *Journal of Economic Dynamics and Control* . [[CrossRef](#)]
12. Karin Kolis, Juhana Hiironen, Kirsikka Riekkinen, Arvo Vitikainen. 2017. Forest land consolidation and its effect on climate. *Land Use Policy* **61**, 536-542. [[CrossRef](#)]
13. Ross McKittrick. 2017. Global energy subsidies: An analytical taxonomy. *Energy Policy* **101**, 379-385. [[CrossRef](#)]
14. Rayleigh Lei, Andrew Gelman, Yair Ghitza. 2017. The 2008 election: A preregistered replication analysis. *Statistics and Public Policy* 0-0. [[CrossRef](#)]
15. T. Banerjee, M. Kumar, N. Singh Aerosol, Climate, and Sustainability . [[CrossRef](#)]
16. Panagiotis Fragkos, Nikos Tasios, Leonidas Paroussos, Pantelis Capros, Stella Tsani. 2017. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. *Energy Policy* **100**, 216-226. [[CrossRef](#)]
17. Karen E. Alexander, William B. Leavenworth, Theodore V. Willis, Carolyn Hall, Steven Mattocks, Steven M. Bittner, Emily Klein, Michelle Staudinger, Alexander Bryan, Julianne Rosset, Benjamin H. Carr, Adrian Jordaan. 2017. Tambora and the mackerel year: Phenology and fisheries during an extreme climate event. *Science Advances* **3**:1, e1601635. [[CrossRef](#)]
18. Jiliang Ma, Jean-Francois Maystadt. 2017. The impact of weather variations on maize yields and household income: Income diversification as adaptation in rural China. *Global Environmental Change* **42**, 93-106. [[CrossRef](#)]
19. Tassilo Herrschel, Peter Newman Cities and the Changing Nature of International Governance 51-106. [[CrossRef](#)]

20. Lynnda Kiess, Natalie Aldern, Saskia de Pee, Martin W. Bloem. Nutrition in Humanitarian Crises 647-664. [\[CrossRef\]](#)
21. Robi Kurniawan, Shunsuke Managi. 2017. Sustainable Development and Performance Measurement: Global Productivity Decomposition. *Sustainable Development* . [\[CrossRef\]](#)
22. Nikolai Hoberg, Stefan Baumgärtner. 2017. Irreversibility and uncertainty cause an intergenerational equity-efficiency trade-off. *Ecological Economics* **131**, 75-86. [\[CrossRef\]](#)
23. Kent Kovacs, Grant West. 2016. The Influence of Groundwater Depletion from Irrigated Agriculture on the Tradeoffs between Ecosystem Services and Economic Returns. *PLOS ONE* **11**:12, e0168681. [\[CrossRef\]](#)
24. Jeroen C. J. M. van den Bergh, W. J. Wouter Botzen. 2016. Global impact of a climate treaty if the Human Development Index replaces GDP as a welfare proxy. *Climate Policy* 1-10. [\[CrossRef\]](#)
25. Lakkanagouda Patil, Basappa Kaliwal. 2016. Effect of CO<sub>2</sub> Concentration on Growth and Biochemical Composition of Newly Isolated Indigenous Microalga *Scenedesmus bajacalifornicus* BBKLP-07. *Applied Biochemistry and Biotechnology* . [\[CrossRef\]](#)
26. Annageldy Arazmuradov. 2016. Economic prospect on carbon emissions in Commonwealth of Independent States. *Economic Change and Restructuring* **49**:4, 395-427. [\[CrossRef\]](#)
27. Beatriz Azevedo de Almeida, Ali Mostafavi. 2016. Resilience of Infrastructure Systems to Sea-Level Rise in Coastal Areas: Impacts, Adaptation Measures, and Implementation Challenges. *Sustainability* **8**:11, 1115. [\[CrossRef\]](#)
28. Kent Kovacs, Ying Xu, Grant West, Michael Popp. 2016. The Tradeoffs between Market Returns from Agricultural Crops and Non-Market Ecosystem Service Benefits on an Irrigated Agricultural Landscape in the Presence of Groundwater Overdraft. *Water* **8**:11, 501. [\[CrossRef\]](#)
29. Grischa Perino, Maximilian Willner. 2016. Procrastinating reform: The impact of the market stability reserve on the EU ETS. *Journal of Environmental Economics and Management* **80**, 37-52. [\[CrossRef\]](#)
30. James D. Ward, Paul C. Sutton, Adrian D. Werner, Robert Costanza, Steve H. Mohr, Craig T. Simmons. 2016. Is Decoupling GDP Growth from Environmental Impact Possible?. *PLOS ONE* **11**:10, e0164733. [\[CrossRef\]](#)
31. Solomon Hsiang. 2016. Climate Econometrics. *Annual Review of Resource Economics* **8**:1, 43-75. [\[CrossRef\]](#)
32. Rintaro Yamaguchi, Masayuki Sato, Kazuhiro Ueta. 2016. Measuring Regional Wealth and Assessing Sustainable Development: An Application to a Disaster-Torn Region in Japan. *Social Indicators Research* **129**:1, 365-389. [\[CrossRef\]](#)
33. Lars Hein, C.S.A. (Kris) van Koppen, Ekko C. van Ierland, Jakob Leidekker. 2016. Temporal scales, ecosystem dynamics, stakeholders and the valuation of ecosystems services. *Ecosystem Services* **21**, 109-119. [\[CrossRef\]](#)
34. Michael Schmeltz, Elisaveta Petkova, Janet Gamble. 2016. Economic Burden of Hospitalizations for Heat-Related Illnesses in the United States, 2001-2010. *International Journal of Environmental Research and Public Health* **13**:9, 894. [\[CrossRef\]](#)
35. Robert G. Chambers, Tigran Melkonyan. 2016. Ambiguity, Reasoned Determination, and Climate-Change Policy. *Journal of Environmental Economics and Management* . [\[CrossRef\]](#)
36. John Hassler, Per Krusell, Jonas Nycander. 2016. Climate policy. *Economic Policy* **31**:87, 503-558. [\[CrossRef\]](#)
37. Geoffrey Heal, Jisung Park. 2016. Reflections—Temperature Stress and the Direct Impact of Climate Change: A Review of an Emerging Literature. *Review of Environmental Economics and Policy* **10**:2, 347-362. [\[CrossRef\]](#)
38. Caizhi Sun, Song Wang, Wei Zou. 2016. Chinese marine ecosystem services value: Regional and structural equilibrium analysis. *Ocean & Coastal Management* **125**, 70-83. [\[CrossRef\]](#)
39. Gustav Engström. 2016. Structural and climatic change. *Structural Change and Economic Dynamics* **37**, 62-74. [\[CrossRef\]](#)

40. S. Niggol Seo. 2016. The Micro-behavioral Framework for Estimating Total Damage of Global Warming on Natural Resource Enterprises with Full Adaptations. *Journal of Agricultural, Biological, and Environmental Statistics* 21:2, 328-347. [[CrossRef](#)]
41. Peter Heindl, Philipp Kanschik. 2016. Ecological sufficiency, individual liberties, and distributive justice: Implications for policy making. *Ecological Economics* 126, 42-50. [[CrossRef](#)]
42. David Anthoff, Francisco Estrada, Richard S. J. Tol. 2016. Shutting Down the Thermohaline Circulation. *American Economic Review* 106:5, 602-606. [[Abstract](#)] [[View PDF article](#)] [[PDF with links](#)]
43. David S. Timmons, Thomas Buchholz, Conor H. Veeneman. 2016. Forest biomass energy: assessing atmospheric carbon impacts by discounting future carbon flows. *GCB Bioenergy* 8:3, 631-643. [[CrossRef](#)]
44. Hans Gersbach, Noemi Hummel. 2016. A development-compatible refunding scheme for a climate treaty. *Resource and Energy Economics* 44, 139-168. [[CrossRef](#)]
45. CHANG SEUNG, JAMES IANELLI. 2016. REGIONAL ECONOMIC IMPACTS OF CLIMATE CHANGE: A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS FOR AN ALASKA FISHERY. *Natural Resource Modeling* 29:2, 289-333. [[CrossRef](#)]
46. Inge van den Bijgaart, Reyer Gerlagh, Matti Liski. 2016. A simple formula for the social cost of carbon. *Journal of Environmental Economics and Management* 77, 75-94. [[CrossRef](#)]
47. Servaas Storm. 2016. How the Invisible Hand is Supposed to Adjust the Natural Thermostat: A Guide for the Perplexed. *Science and Engineering Ethics* . [[CrossRef](#)]
48. In Chang Hwang, Richard S.J. Tol, Marjan W. Hofkes. 2016. Fat-tailed risk about climate change and climate policy. *Energy Policy* 89, 25-35. [[CrossRef](#)]
49. Xiang Zou, Muhammad Azam, Talat Islam, Khalid Zaman. 2016. Environment and air pollution like gun and bullet for low-income countries: war for better health and wealth. *Environmental Science and Pollution Research* 23:4, 3641-3657. [[CrossRef](#)]
50. RICHARD S. J. TOL. 2016. THE IMPACTS OF CLIMATE CHANGE ACCORDING TO THE IPCC. *Climate Change Economics* 07:01, 1640004. [[CrossRef](#)]
51. Scott G. Cole, Per-Olav Moksnes. 2016. Valuing Multiple Eelgrass Ecosystem Services in Sweden: Fish Production and Uptake of Carbon and Nitrogen. *Frontiers in Marine Science* 2. . [[CrossRef](#)]
52. Gregory N. Price, Juliet U. Elu. 2016. Can Black Africa afford to be Green Africa?. *Journal of Economic Studies* 43:1, 48-58. [[CrossRef](#)]
53. Richard Millar, Myles Allen, Joeri Rogelj, Pierre Friedlingstein. 2016. The cumulative carbon budget and its implications. *Oxford Review of Economic Policy* 32:2, 323-342. [[CrossRef](#)]
54. Elettra Agliardi, Mehmet Pinar, Thanasis Stengos. 2016. Air and water pollution over time and industries with stochastic dominance. *Stochastic Environmental Research and Risk Assessment* . [[CrossRef](#)]
55. Francesca Bottalico, Lucia Pesola, Matteo Vizzarri, Leonardo Antonello, Anna Barbati, Gherardo Chirici, Piermaria Corona, Sebastiano Cullotta, Vittorio Garfi, Vincenzo Giannico, Raffaele Laforteza, Fabio Lombardi, Marco Marchetti, Susanna Nocentini, Francesco Riccioli, Davide Travaglini, Lorenzo Sallustio. 2016. Modeling the influence of alternative forest management scenarios on wood production and carbon storage: A case study in the Mediterranean region. *Environmental Research* 144, 72-87. [[CrossRef](#)]
56. Nick Hanley, Louis Dupuy, Eoin McLaughlin 213. [[CrossRef](#)]
57. Paul J. Thomassin, Ning An The Economic Impact of Climate Change on Cash Crop Farms in Québec and Ontario 71-89. [[CrossRef](#)]
58. Mariève Lafontaine-Messier, Nancy Gélinas, Alain Olivier. 2016. Profitability of food trees planted in urban public green areas. *Urban Forestry & Urban Greening* 16, 197-207. [[CrossRef](#)]
59. Tommi Ekholm. 2016. Optimal forest rotation age under efficient climate change mitigation. *Forest Policy and Economics* 62, 62-68. [[CrossRef](#)]
60. Christopher Monckton of Benchley Is CO2 Mitigation Cost Effective? 175-187. [[CrossRef](#)]

61. J. Hassler, P. Krusell, A.A. Smith. Environmental Macroeconomics 1893–2008. [[CrossRef](#)]
62. Kai Lessmann, Ulrike Kornek, Valentina Bosetti, Rob Dellink, Johannes Emmerling, Johan Eyckmans, Miyuki Nagashima, Hans-Peter Weikard, Zili Yang. 2015. The Stability and Effectiveness of Climate Coalitions. *Environmental and Resource Economics* **62**:4, 811–836. [[CrossRef](#)]
63. Marika Arena, Antonio Conte, Marco Melacini. 2015. Linking environmental accounting to reward systems: the case of the Environmental Profit and Loss Account. *Journal of Cleaner Production* **108**, 625–636. [[CrossRef](#)]
64. Dominik Jasinski, James Meredith, Kerry Kirwan. 2015. A comprehensive review of full cost accounting methods and their applicability to the automotive industry. *Journal of Cleaner Production* **108**, 1123–1139. [[CrossRef](#)]
65. Stephen Polasky, Benjamin Bryant, Peter Hawthorne, Justin Johnson, Bonnie Keeler, Derric Pennington. 2015. Inclusive Wealth as a Metric of Sustainable Development. *Annual Review of Environment and Resources* **40**:1, 445–466. [[CrossRef](#)]
66. Jennifer M. Alix-Garcia, Katharine R. E. Sims, Patricia Yañez-Pagans. 2015. Only One Tree from Each Seed? Environmental Effectiveness and Poverty Alleviation in Mexico's Payments for Ecosystem Services Program. *American Economic Journal: Economic Policy* **7**:4, 1–40. [[Abstract](#)] [[View PDF article](#)] [[PDF with links](#)]
67. Abayomi Oyekale. 2015. Access to Risk Mitigating Weather Forecasts and Changes in Farming Operations in East and West Africa: Evidence from a Baseline Survey. *Sustainability* **7**:11, 14599–14617. [[CrossRef](#)]
68. FRANCISCO ESTRADA, RICHARD S. J. TOL. 2015. TOWARD IMPACT FUNCTIONS FOR STOCHASTIC CLIMATE CHANGE. *Climate Change Economics* **06**:04, 1550015. [[CrossRef](#)]
69. Silvio Nocera, Stefania Tonin, Federico Cavallaro. 2015. Carbon estimation and urban mobility plans: Opportunities in a context of austerity. *Research in Transportation Economics* **51**, 71–82. [[CrossRef](#)]
70. Nick Hanley, Louis Dupuy, Eoin McLaughlin. 2015. GENUINE SAVINGS AND SUSTAINABILITY. *Journal of Economic Surveys* **29**:4, 779–806. [[CrossRef](#)]
71. L. Sallustio, V. Quatrini, D. Geneletti, P. Corona, M. Marchetti. 2015. Assessing land take by urban development and its impact on carbon storage: Findings from two case studies in Italy. *Environmental Impact Assessment Review* **54**, 80–90. [[CrossRef](#)]
72. David Zilberman. 2015. Editorial — The Economics of Climate Change and Water: An Introduction to the Special Issue. *Water Economics and Policy* **01**:03, 1502001. [[CrossRef](#)]
73. Derek Lemoine, Sarah Kapnick. 2015. A top-down approach to projecting market impacts of climate change. *Nature Climate Change* **6**:1, 51–55. [[CrossRef](#)]
74. Hagen Schulte in den Bäumen, Johannes Többen, Manfred Lenzen. 2015. Labour forced impacts and production losses due to the 2013 flood in Germany. *Journal of Hydrology* **527**, 142–150. [[CrossRef](#)]
75. Katie Jenkins, Rachel Warren. 2015. Drought-Damage Functions for the Estimation of Drought Costs under Future Projections of Climate Change. *Journal of Extreme Events* **02**:01, 1550001. [[CrossRef](#)]
76. David L. Kelly, Zhuo Tan. 2015. Learning and climate feedbacks: Optimal climate insurance and fat tails. *Journal of Environmental Economics and Management* **72**, 98–122. [[CrossRef](#)]
77. Jon D. Pelletier, A. Brad Murray, Jennifer L. Pierce, Paul R. Bierman, David D. Breshears, Benjamin T. Crosby, Michael Ellis, Efi Foufoula-Georgiou, Arjun M. Heimsath, Chris Houser, Nick Lancaster, Marco Marani, Dorothy J. Merritts, Laura J. Moore, Joel L. Pederson, Michael J. Poulos, Tammy M. Rittenour, Joel C. Rowland, Peter Ruggiero, Dylan J. Ward, Andrew D. Wickert, Elowyn M. Yager. 2015. Forecasting the response of Earth's surface to future climatic and land use changes: A review of methods and research needs. *Earth's Future* **3**:7, 220–251. [[CrossRef](#)]
78. Francisco Estrada, Richard S.J. Tol, Carlos Gay-García. 2015. The persistence of shocks in GDP and the estimation of the potential economic costs of climate change. *Environmental Modelling & Software* **69**, 155–165. [[CrossRef](#)]

79. S. Niggol Seo. 2015. Adaptation to Global Warming as an Optimal Transition Process to A Greenhouse World. *Economic Affairs* **35**:2, 272-284. [[CrossRef](#)]
80. J.C.J.M. van den Bergh, W.J.W. Botzen. 2015. Monetary valuation of the social cost of CO2 emissions: A critical survey. *Ecological Economics* **114**, 33-46. [[CrossRef](#)]
81. David R. Morrow. 2015. Wants and needs in mitigation policy. *Climatic Change* **130**:3, 335-345. [[CrossRef](#)]
82. Yan Tan, Xuchun Liu, Graeme Hugo. 2015. Exploring relationship between social inequality and adaptations to climate change: evidence from urban household surveys in the Yangtze River delta, China. *Population and Environment* **36**:4, 400-428. [[CrossRef](#)]
83. Ian W. H. Parry, Govinda R. Timilsina. 2015. Demand-Side Instruments to Reduce Road Transportation Externalities in the Greater Cairo Metropolitan Area. *International Journal of Sustainable Transportation* **9**:3, 203-216. [[CrossRef](#)]
84. Ottmar Edenhofer, Michael Jakob, Felix Creutzig, Christian Flachsland, Sabine Fuss, Martin Kowarsch, Kai Lessmann, Linus Mattauch, Jan Siegmeier, Jan Christoph Steckel. 2015. Closing the emission price gap. *Global Environmental Change* **31**, 132-143. [[CrossRef](#)]
85. Susan Spierre Clark, Thomas P. Seager, Evan Selinger. 2015. A development-based approach to global climate policy. *Environment Systems and Decisions* **35**:1, 1-10. [[CrossRef](#)]
86. Eugene Y.C. Wong, Allen H. Tai, Henry Y.K. Lau, Mardjuki Raman. 2015. An utility-based decision support sustainability model in slow steaming maritime operations. *Transportation Research Part E: Logistics and Transportation Review* . [[CrossRef](#)]
87. Paul Cashin, Kamiar Mohaddes, Mehdi Raissi. 2015. Fair Weather or Foul? The Macroeconomic Effects of El Niño. *IMF Working Papers* **15**:89, 1. [[CrossRef](#)]
88. Christian Dienes. 2015. Actions and intentions to pay for climate change mitigation: Environmental concern and the role of economic factors. *Ecological Economics* **109**, 122-129. [[CrossRef](#)]
89. Marshall Burke, Solomon M. Hsiang, Edward Miguel. 2015. Global non-linear effect of temperature on economic production. *Nature* **527**:7577, 235. [[CrossRef](#)]
90. Silvio Nocera, Stefania Tonin, Federico Cavallaro. 2015. The economic impact of greenhouse gas abatement through a meta-analysis: Valuation, consequences and implications in terms of transport policy. *Transport Policy* **37**, 31-43. [[CrossRef](#)]
91. Gennaro D'Amato, Stephen T. Holgate, Ruby Pawankar, Dennis K. Ledford, Lorenzo Cecchi, Mona Al-Ahmad, Fatma Al-Enezi, Saleh Al-Muhsen, Ignacio Ansotegui, Carlos E. Baena-Cagnani, David J. Baker, Hasan Bayram, Karl Christian Bergmann, Louis-Philippe Boulet, Jeroen T. M. Buters, Maria D'Amato, Sofia Dorsano, Jeroen Douwes, Sarah Elise Finlay, Donata Garrasi, Maximiliano Gómez, Tari Haahtela, Rabih Halwani, Youssouf Hassani, Basam Mahboub, Guy Marks, Paola Michelozzi, Marcello Montagni, Carlos Nunes, Jay Jae-Won Oh, Todor A. Popov, Jay Portnoy, Erminia Ridolo, Nelson Rosário, Menachem Rottem, Mario Sánchez-Borges, Elopy Sibanda, Juan José Sienra-Monge, Carolina Vitale, Isabella Annesi-Maesano. 2015. Meteorological conditions, climate change, new emerging factors, and asthma and related allergic disorders. A statement of the World Allergy Organization. *World Allergy Organization Journal* **8**:1. . [[CrossRef](#)]
92. Zhonghua Shen, Kazumi Wakita, Taro Oishi, Nobuyuki Yagi, Hisashi Kurokura, Robert Blasiak, Ken Furuya. 2015. Willingness to pay for ecosystem services of open oceans by choice-based conjoint analysis: A case study of Japanese residents. *Ocean & Coastal Management* **103**, 1-8. [[CrossRef](#)]
93. Christopher W. Tessum, Jason D. Hill, Julian D. Marshall. 2014. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proceedings of the National Academy of Sciences* 201406853. [[CrossRef](#)]
94. Paul A. T. Higgins, Jonah V. Steinbuck. 2014. A Conceptual Tool for Climate Change Risk Assessment. *Earth Interactions* **18**:21, 1-15. [[CrossRef](#)]



95. L.R. Carrasco, S.K. Papworth. 2014. A ranking of net national contributions to climate change mitigation through tropical forest conservation. *Journal of Environmental Management* **146**, 575-581. [[CrossRef](#)]
96. Tommi Ekholm. 2014. Hedging the climate sensitivity risks of a temperature target. *Climatic Change* **127**:2, 153-167. [[CrossRef](#)]
97. Tommi Ekholm, Niko Karvosenoja, Jarkko Tissari, Laura Sokka, Kaarle Kupiainen, Olli Sippula, Mikko Savolahti, Jorma Jokiniemi, Ilkka Savolainen. 2014. A multi-criteria analysis of climate, health and acidification impacts due to greenhouse gases and air pollution—The case of household-level heating technologies. *Energy Policy* **74**, 499-509. [[CrossRef](#)]
98. John C.V. Pezzey, Paul J. Burke. 2014. Towards a more inclusive and precautionary indicator of global sustainability. *Ecological Economics* **106**, 141-154. [[CrossRef](#)]
99. Paul A. T. Higgins. 2014. How to deal with climate change. *Physics Today* **67**:10, 32-37. [[CrossRef](#)]
100. Melissa Dell, Benjamin F. Jones, Benjamin A. Olken. 2014. What Do We Learn from the Weather? The New Climate-Economy Literature. *Journal of Economic Literature* **52**:3, 740-798. [[Abstract](#)] [[View PDF article](#)] [[PDF with links](#)]
101. Marc D. Davidson. 2014. Zero discounting can compensate future generations for climate damage. *Ecological Economics* **105**, 40-47. [[CrossRef](#)]
102. J. A. Johnson, C. F. Runge, B. Senauer, J. Foley, S. Polasky. 2014. Global agriculture and carbon trade-offs. *Proceedings of the National Academy of Sciences* **111**:34, 12342-12347. [[CrossRef](#)]
103. A. Mekonnen. 2014. Economic Costs of Climate Change and Climate Finance with a Focus on Africa. *Journal of African Economies* **23**:suppl 2, ii50-ii82. [[CrossRef](#)]
104. Hartmut Fünfgeld, Darryn McEvoy. 2014. Frame Divergence in Climate Change Adaptation Policy: Insights from Australian Local Government Planning. *Environment and Planning C: Government and Policy* **32**:4, 603-622. [[CrossRef](#)]
105. J. Zake, M. Hauser. 2014. Farmers' perceptions of implementation of climate variability disaster preparedness strategies in Central Uganda. *Environmental Hazards* **13**:3, 248-266. [[CrossRef](#)]
106. Benjamin Crost, Christian P. Traeger. 2014. Optimal CO<sub>2</sub> mitigation under damage risk valuation. *Nature Climate Change* **4**:7, 631-636. [[CrossRef](#)]
107. Richard S. J. Tol. 2014. Bootstraps for Meta-Analysis with an Application to the Impact of Climate Change. *Computational Economics* . [[CrossRef](#)]
108. Sujata Manandhar, Vishnu Pandey, Futaba Kazama, So Kazama. Economics of Climate Change 153-182. [[CrossRef](#)]
109. Frans Berkhout, Bart van den Hurk, Janette Bessembinder, Joop de Boer, Bram Bregman, Michiel van Drunen. 2014. Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments. *Regional Environmental Change* **14**:3, 879-893. [[CrossRef](#)]
110. Richard S. J. Tol. 2014. Correction and Update: The Economic Effects of Climate Change. *Journal of Economic Perspectives* **28**:2, 221-226. [[Abstract](#)] [[View PDF article](#)] [[PDF with links](#)]
111. Matthew Ranson. 2014. Crime, weather, and climate change. *Journal of Environmental Economics and Management* **67**:3, 274-302. [[CrossRef](#)]
112. W. J. Wouter Botzen, Jeroen C. J. M. van den Bergh. 2014. Specifications of Social Welfare in Economic Studies of Climate Policy: Overview of Criteria and Related Policy Insights. *Environmental and Resource Economics* **58**:1, 1-33. [[CrossRef](#)]
113. Hassan Bencheikroun, Amrita Ray Chaudhuri. 2014. Transboundary pollution and clean technologies. *Resource and Energy Economics* **36**:2, 601-619. [[CrossRef](#)]
114. Yuan Feng, Xi Chen, Xi Frank Xu. 2014. Current status and potentials of enhanced geothermal system in China: A review. *Renewable and Sustainable Energy Reviews* **33**, 214-223. [[CrossRef](#)]
115. Stephan Lewandowsky, James S. Risbey, Michael Smithson, Ben R. Newell, John Hunter. 2014. Scientific uncertainty and climate change: Part I. Uncertainty and unabated emissions. *Climatic Change* . [[CrossRef](#)]



116. James Blignaut, James Aronson, Rudolf de Groot. 2014. Restoration of natural capital: A key strategy on the path to sustainability. *Ecological Engineering* **65**, 54–61. [[CrossRef](#)]
117. Timothy J. Garrett. 2014. Long-run evolution of the global economy: 1. Physical basis. *Earth's Future* **2**:3, 127–151. [[CrossRef](#)]
118. J. C. J. M. van den Bergh, W. J. W. Botzen. 2014. A lower bound to the social cost of CO2 emissions. *Nature Climate Change* **4**:4, 253–258. [[CrossRef](#)]
119. Johannes Diederich, Timo Goeschl. 2014. Willingness to Pay for Voluntary Climate Action and Its Determinants: Field-Experimental Evidence. *Environmental and Resource Economics* **57**:3, 405–429. [[CrossRef](#)]
120. William Nordhaus. 2014. Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists* **1**:1/2, 273–312. [[CrossRef](#)]
121. Paul M. Peeters, Eke Eijgelaar. 2014. Tourism's climate mitigation dilemma: Flying between rich and poor countries. *Tourism Management* **40**, 15–26. [[CrossRef](#)]
122. Kyoungmi Lee, Hee-Jeong Baek, ChunHo Cho. 2014. The Estimation of Base Temperature for Heating and Cooling Degree-Days for South Korea. *Journal of Applied Meteorology and Climatology* **53**:2, 300–309. [[CrossRef](#)]
123. Mingxi Wang, Mingrong Wang, Chuanyin Dang, Shouyang Wang. 2014. A Pareto Optimal Auction Mechanism for Carbon Emission Rights. *Mathematical Problems in Engineering* **2014**, 1–7. [[CrossRef](#)]
124. Joseph E. Aldy, W. Kip Viscusi. Environmental Risk and Uncertainty 601–649. [[CrossRef](#)]
125. Jan Kunnas, Eoin McLaughlin, Nick Hanley, David Greasley, Les Oxley, Paul Warde. 2014. Counting carbon: historic emissions from fossil fuels, long-run measures of sustainable development and carbon debt. *Scandinavian Economic History Review* **62**:3, 243. [[CrossRef](#)]
126. Juhana Hiironen, Kirsikka Niukkanen. 2014. On the structural development of arable land in Finland – How costly will it be for the climate?. *Land Use Policy* **36**, 192–198. [[CrossRef](#)]
127. Koji Tokimatsu, Rieko Yasuoka, Masahiro Nishio, Kazuhiro Ueta. 2013. Sustainability and the measurement of future paths in genuine savings: case studies. *International Journal of Sustainable Development & World Ecology* 1–12. [[CrossRef](#)]
128. José A. Tapia Granados, Óscar Carpintero. 2013. Economic Aspects of Climate Change. *Journal of Crop Improvement* **27**:6, 693–734. [[CrossRef](#)]
129. Mingxi Wang, Yi Hu, Haibin Xie, Mingrong Wang. Carbon Emission Abatement: An Introduction 369–372. [[CrossRef](#)]
130. Francisco Estrada, Elissaios Papyrakis, Richard S. J. Tol, Carlos Gay-Garcia. 2013. The economics of climate change in Mexico: implications for national/regional policy. *Climate Policy* **13**:6, 738–750. [[CrossRef](#)]
131. In Chang Hwang, Frédéric Reynès, Richard S. J. Tol. 2013. Climate Policy Under Fat-Tailed Risk: An Application of Dice. *Environmental and Resource Economics* **56**:3, 415–436. [[CrossRef](#)]
132. Rohani Mohd Shah, Zaliha Husin. 2013. Policy Integration: Internationalization of State Environmental Protection Policy. *Procedia - Social and Behavioral Sciences* **101**, 292–298. [[CrossRef](#)]
133. Rob Dellink, Thijs Dekker, Janina Ketterer. 2013. The Fatter the Tail, the Fatter the Climate Agreement. *Environmental and Resource Economics* **56**:2, 277–305. [[CrossRef](#)]
134. Derek Lemoine, Haewon C McJeon. 2013. Trapped between two tails: trading off scientific uncertainties via climate targets. *Environmental Research Letters* **8**:3, 034019. [[CrossRef](#)]
135. Sebastiano Cupertino. 2013. Cost-benefit analysis of carbon dioxide capture and storage considering the impact of two different climate change mitigation regimes. *ECONOMICS AND POLICY OF ENERGY AND THE ENVIRONMENT* :1, 73–89. [[CrossRef](#)]

136. R. Warren, J. A. Lowe, N. W. Arnell, C. Hope, P. Berry, S. Brown, A. Gambhir, S. N. Gosling, R. J. Nicholls, J. O'Hanley, T. J. Osborn, T. Osborne, J. Price, S. C. B. Raper, G. Rose, J. Vanderwal. 2013. The AVOID programme's new simulations of the global benefits of stringent climate change mitigation. *Climatic Change* . [\[CrossRef\]](#)
137. Sharachchandra Lele, Veena Srinivasan. 2013. Disaggregated economic impact analysis incorporating ecological and social trade-offs and techno-institutional context: A case from the Western Ghats of India. *Ecological Economics* **91**, 98-112. [\[CrossRef\]](#)
138. Léa Tardieu, Sébastien Roussel, Jean-Michel Salles. 2013. Assessing and mapping global climate regulation service loss induced by Terrestrial Transport Infrastructure construction. *Ecosystem Services* **4**, 73-81. [\[CrossRef\]](#)
139. Richard S.J. Tol. 2013. Targets for global climate policy: An overview. *Journal of Economic Dynamics and Control* **37**:5, 911-928. [\[CrossRef\]](#)
140. K. A. Konrad, M. Thum. 2013. The Role of Economic Policy in Climate Change Adaptation. *CESifo Economic Studies* . [\[CrossRef\]](#)
141. Bernward Gesang. 2013. What Climate Policy Can a Utilitarian Justify?. *Journal of Agricultural and Environmental Ethics* **26**:2, 377-392. [\[CrossRef\]](#)
142. Stefan Speck. 2013. Carbon taxation: two decades of experience and future prospects. *Carbon Management* **4**:2, 171-183. [\[CrossRef\]](#)
143. José Granados, Óscar Carpintero Dynamics and Economic Aspects of Climate Change 29-58. [\[CrossRef\]](#)
144. Dennis Mares. 2013. Climate change and crime: monthly temperature and precipitation anomalies and crime rates in St. Louis, MO 1990-2009. *Crime, Law and Social Change* **59**:2, 185-208. [\[CrossRef\]](#)
145. Richard S.J. Tol. 2013. Climate policy with Bentham-Rawls preferences. *Economics Letters* **118**:3, 424-428. [\[CrossRef\]](#)
146. Luís C. Rodrigues, Jeroen C.J.M. van den Bergh, Andrea Ghermandi. 2013. Socio-economic impacts of ocean acidification in the Mediterranean Sea. *Marine Policy* **38**, 447-456. [\[CrossRef\]](#)
147. S. Niggol Seo. 2013. Economics of global warming as a global public good: Private incentives and smart adaptations. *Regional Science Policy & Practice* **5**:1, 83-95. [\[CrossRef\]](#)
148. David Anthoff, Richard S. J. Tol. 2013. The uncertainty about the social cost of carbon: A decomposition analysis using fund. *Climatic Change* . [\[CrossRef\]](#)
149. Donald McCubbin, Benjamin K. Sovacool. 2013. Quantifying the health and environmental benefits of wind power to natural gas. *Energy Policy* **53**, 429-441. [\[CrossRef\]](#)
150. Oliver Schenker. 2013. Exchanging Goods and Damages: The Role of Trade on the Distribution of Climate Change Costs. *Environmental and Resource Economics* **54**:2, 261-282. [\[CrossRef\]](#)
151. George A. Backus, Thomas S. Lowry, Drake E. Warren. 2013. The near-term risk of climate uncertainty among the U.S. states. *Climatic Change* **116**:3-4, 495-522. [\[CrossRef\]](#)
152. Partha Dasgupta. 2013. National Wealth. *Population and Development Review* **38**, 243-264. [\[CrossRef\]](#)
153. R.L. Gordon Coal: Prospects in the Twenty-First Century: Exhaustion Trumped by Global Warming? 137-145. [\[CrossRef\]](#)
154. A. K. M. Ahsan Ullah The Interplay between Climate Change, Economy and Displacement: Experience from Asia 38-55. [\[CrossRef\]](#)
155. William Nordhaus Integrated Economic and Climate Modeling 1069-1131. [\[CrossRef\]](#)
156. Malte Grossmann, Ottfried Dietrich. 2012. SOCIAL BENEFITS AND ABATEMENT COSTS OF GREENHOUSE GAS EMISSION REDUCTIONS FROM RESTORING DRAINED FEN WETLANDS: A CASE STUDY FROM THE ELBE RIVER BASIN (GERMANY). *Irrigation and Drainage* **61**:5, 691-704. [\[CrossRef\]](#)

157. Milan Ščasný, Anna Alberini. 2012. Valuation of Mortality Risk Attributable to Climate Change: Investigating the Effect of Survey Administration Modes on a VSL. *International Journal of Environmental Research and Public Health* **9**:12, 4760-4781. [[CrossRef](#)]
158. Christopher Guo, Christopher Costello. 2012. The value of adaption: Climate change and timberland management. *Journal of Environmental Economics and Management* . [[CrossRef](#)]
159. Wen Shwo Fang, Stephen M. Miller, Chih-Chuan Yeh. 2012. The effect of ESCOs on energy use. *Energy Policy* **51**, 558-568. [[CrossRef](#)]
160. Peter A. Victor. 2012. Growth, degrowth and climate change: A scenario analysis. *Ecological Economics* **84**, 206-212. [[CrossRef](#)]
161. Richard S. J. Tol. 2012. The economic impact of climate change in the 20th and 21st centuries. *Climatic Change* . [[CrossRef](#)]
162. Richard S.J. Tol. 2012. A cost-benefit analysis of the EU 20/20/2020 package. *Energy Policy* **49**, 288-295. [[CrossRef](#)]
163. Richard S. J. Tol. 2012. On the Uncertainty About the Total Economic Impact of Climate Change. *Environmental and Resource Economics* **53**:1, 97-116. [[CrossRef](#)]
164. Channing Arndt, Paul Chinowsky, Sherman Robinson, Kenneth Strzepek, Finn Tarp, James Thurlow. 2012. Economic Development under Climate Change. *Review of Development Economics* **16**:3, 369-377. [[CrossRef](#)]
165. James Thurlow, Paul Dorosh, Winston Yu. 2012. A Stochastic Simulation Approach to Estimating the Economic Impacts of Climate Change in Bangladesh. *Review of Development Economics* **16**:3, 412-428. [[CrossRef](#)]
166. David Zilberman, Jinhua Zhao, Amir Heiman. 2012. Adoption Versus Adaptation, with Emphasis on Climate Change. *Annual Review of Resource Economics* **4**:1, 27-53. [[CrossRef](#)]
167. Kris A. Johnson, Stephen Polasky, Erik Nelson, Derric Pennington. 2012. Uncertainty in ecosystem services valuation and implications for assessing land use tradeoffs: An agricultural case study in the Minnesota River Basin. *Ecological Economics* **79**, 71-79. [[CrossRef](#)]
168. Xiao Chen, Alan Woodland. 2012. International trade and climate change. *International Tax and Public Finance* . [[CrossRef](#)]
169. Robin M. Leichenko, Adelle Thomas. 2012. Coastal Cities and Regions in a Changing Climate: Economic Impacts, Risks and Vulnerabilities. *Geography Compass* **6**:6, 327-339. [[CrossRef](#)]
170. Kenneth J. Arrow, Partha Dasgupta, Lawrence H. Goulder, Kevin J. Mumford, Kirsten Oleson. 2012. Sustainability and the measurement of wealth. *Environment and Development Economics* **17**:03, 317-353. [[CrossRef](#)]
171. S. Niggol Seo. 2012. WHAT ELUDES INTERNATIONAL AGREEMENTS ON CLIMATE CHANGE? THE ECONOMICS OF GLOBAL PUBLIC GOODS. *Economic Affairs* **32**:2, 74-80. [[CrossRef](#)]
172. Frank W. Larsen, Will R. Turner, Thomas M. Brooks. 2012. Conserving Critical Sites for Biodiversity Provides Disproportionate Benefits to People. *PLoS ONE* **7**:5, e36971. [[CrossRef](#)]
173. SOLOMON M. HSIANG, DAIJU NARITA. 2012. ADAPTATION TO CYCLONE RISK: EVIDENCE FROM THE GLOBAL CROSS-SECTION. *Climate Change Economics* **03**:02, 1250011. [[CrossRef](#)]
174. Eimear Leahy, Richard S. J. Tol. 2012. Greener homes: an ex-post estimate of the cost of carbon dioxide emission reduction using administrative micro-data from the Republic of Ireland. *Environmental Economics and Policy Studies* . [[CrossRef](#)]
175. David C. Holzman. 2012. Accounting for Nature's Benefits: The Dollar Value of Ecosystem Services. *Environmental Health Perspectives* **120**:4, a152-a157. [[CrossRef](#)]

176. Malte Grossmann, Ottfried Dietrich. 2012. Integrated Economic-Hydrologic Assessment of Water Management Options for Regulated Wetlands Under Conditions of Climate Change: A Case Study from the Spreewald (Germany). *Water Resources Management* . [\[CrossRef\]](#)
177. WILLIAM D. NORDHAUS. 2012. Economic Policy in the Face of Severe Tail Events. *Journal of Public Economic Theory* 14:2, 197-219. [\[CrossRef\]](#)
178. S. Polasky, K. Johnson, B. Keeler, K. Kovacs, E. Nelson, D. Pennington, A. J. Plantinga, J. Withey. 2012. Are investments to promote biodiversity conservation and ecosystem services aligned?. *Oxford Review of Economic Policy* 28:1, 139-163. [\[CrossRef\]](#)
179. Anke Reichhuber, Till Requate. 2012. Alternative use systems for the remaining Ethiopian cloud forest and the role of Arabica coffee — A cost-benefit analysis. *Ecological Economics* . [\[CrossRef\]](#)
180. Mingxi Wang, Mingrong Wang, Shouyang Wang. 2012. Optimal investment and uncertainty on China's carbon emission abatement. *Energy Policy* 41, 871-877. [\[CrossRef\]](#)
181. Daiju Narita, Katrin Rehdanz, Richard S. J. Tol. 2012. Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Climatic Change* . [\[CrossRef\]](#)
182. Nathan Rive, Gunnar Myhre. 2012. Communicating the Probabilities of Extreme Surface Temperature Outcomes. *Atmospheric and Climate Sciences* 02:04, 538-545. [\[CrossRef\]](#)
183. Rohani Mohd Shah, Rugayah Hashim, Norha Abu Hanifah. 2012. Antarctic Treaty System and Madrid Protocol 1991: Transformation of Legislation. *APCBEE Procedia* 1, 74-78. [\[CrossRef\]](#)
184. Rohani Mohd Shah, Rugayah Hashim. 2012. "Scientists Paradise": Environmental Sustainability and Policy Governance. *Procedia - Social and Behavioral Sciences* 35, 384-388. [\[CrossRef\]](#)
185. Rohani Mohd Shah, Hamisah Abd. Rahman. 2012. Guarding Antarctic from Global Warming is the Key to Pristine Urban Communities. *Procedia - Social and Behavioral Sciences* 35, 378-383. [\[CrossRef\]](#)
186. Robert S. Pindyck. 2012. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management* . [\[CrossRef\]](#)
187. Economics of Climate Change and Socioeconomic Implications 297-344. [\[CrossRef\]](#)
188. Wim Naudé. 2011. Climate Change and Industrial Policy. *Sustainability* 3:12, 1003-1021. [\[CrossRef\]](#)
189. S. T. Anderson, I. W. H. Parry, J. M. Sallee, C. Fischer. 2011. Automobile Fuel Economy Standards: Impacts, Efficiency, and Alternatives. *Review of Environmental Economics and Policy* 5:1, 89-108. [\[CrossRef\]](#)
190. J. Cui, H. Lapan, G. Moschini, J. Cooper. 2011. Welfare Impacts of Alternative Biofuel and Energy Policies. *American Journal of Agricultural Economics* . [\[CrossRef\]](#)
191. Dieter Helm. 2011. Sustainable Consumption, Climate Change and Future Generations. *Royal Institute of Philosophy Supplement* 69, 235-252. [\[CrossRef\]](#)
192. Lucas Bretschger, Simone Valente. 2011. Climate Change and Uneven Development\*. *The Scandinavian Journal of Economics* no-no. [\[CrossRef\]](#)
193. Richard S.J. Tol. 2011. The Social Cost of Carbon. *Annual Review of Resource Economics* 3:1, 419-443. [\[CrossRef\]](#)
194. Roger N. Jones. 2011. The latest iteration of IPCC uncertainty guidance—an author perspective. *Climatic Change* . [\[CrossRef\]](#)
195. Richard S. J. Tol. 2011. Regulating knowledge monopolies: the case of the IPCC. *Climatic Change* . [\[CrossRef\]](#)
196. David Maddison, Katrin Rehdanz. 2011. The impact of climate on life satisfaction. *Ecological Economics* . [\[CrossRef\]](#)
197. Miyuki Nagashima, Hans-Peter Weikard, Kelly de Bruin, Rob Dellink. 2011. INTERNATIONAL CLIMATE AGREEMENTS UNDER INDUCED TECHNOLOGICAL CHANGE. *Metroeconomica* no-no. [\[CrossRef\]](#)

198. Rolf Färe, Shawna Grosskopf, Dimitri Margaritis, William L. Weber. 2011. Technological change and timing reductions in greenhouse gas emissions. *Journal of Productivity Analysis* . [[CrossRef](#)]
199. Johann Dupuis, Peter Knoepfel. 2011. Les barrières à la mise en œuvre des politiques d'adaptation au changement climatique: le cas de la Suisse. *Swiss Political Science Review* 17:2, 188-219. [[CrossRef](#)]
200. Korbinian P. Freier, Uwe A. Schneider, Manfred Finckh. 2011. Dynamic interactions between vegetation and land use in semi-arid Morocco: Using a Markov process for modeling rangelands under climate change. *Agriculture, Ecosystems & Environment* 140:3-4, 462-472. [[CrossRef](#)]
201. Stephen Polasky, Erik Nelson, Derric Pennington, Kris A. Johnson. 2011. The Impact of Land-Use Change on Ecosystem Services, Biodiversity and Returns to Landowners: A Case Study in the State of Minnesota. *Environmental and Resource Economics* 48:2, 219-242. [[CrossRef](#)]
202. Armon Rezai, Duncan K. Foley, Lance Taylor. 2011. Global warming and economic externalities. *Economic Theory* . [[CrossRef](#)]
203. Hsin Huang, Martin von Lampe, Frank van Tongeren. 2011. Climate change and trade in agriculture###. *Food Policy* 36, S9-S13. [[CrossRef](#)]
204. P. Michael Link, Richard S. J. Tol. 2011. Estimation of the economic impact of temperature changes induced by a shutdown of the thermohaline circulation: an application of FUND. *Climatic Change* 104:2, 287-304. [[CrossRef](#)]
205. Joseph E. Aldy,, Alan J. Krupnick,, Richard G. Newell,, Ian W. H. Parry,, William A. Pizer. 2010. Designing Climate Mitigation Policy. *Journal of Economic Literature* 48:4, 903-934. [[Abstract](#)] [[View PDF article](#)] [[PDF with links](#)]
206. S. M. Hsiang. 2010. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences* 107:35, 15367-15372. [[CrossRef](#)]
207. JODY W. LIPFORD, BRUCE YANDLE. 2010. Environmental Kuznets curves, carbon emissions, and public choice. *Environment and Development Economics* 15:04, 417-438. [[CrossRef](#)]
208. W. D. Nordhaus. 2010. Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences* 107:26, 11721-11726. [[CrossRef](#)]
209. Susan G. Spierre, Thomas Seager, Evan SelingerDetermining an equitable allocation Of global carbon dioxide emissions 1-5. [[CrossRef](#)]
210. G F Nemet, T Holloway, P Meier. 2010. Implications of incorporating air-quality co-benefits into climate change policymaking. *Environmental Research Letters* 5:1, 014007. [[CrossRef](#)]
211. Julie A. Nelson. 2009. Between a rock and a soft place: Ecological and feminist economics in policy debates#. *Ecological Economics* 69:1, 1-8. [[CrossRef](#)]
212. H. Gunatilake, C. Gopalakrishnan, F. D. De Guzman. 2009. Role of the Private Sector in Managing the Asian Environment: A Review. *Journal of Natural Resources Policy Research* 1:4, 335-351. [[CrossRef](#)]