Reason Foundation
Policy Study No. 445
August 2015

Assessing the Social Costs and Benefits of Regulating Carbon Emissions

by Julian Morris

Reason Foundation

Reason Foundation's mission is to advance a free society by developing, applying and promoting libertarian principles, including individual liberty, free markets and the rule of law. We use journalism and public policy research to influence the frameworks and actions of policymakers, journalists and opinion leaders.

Reason Foundation's nonpartisan public policy research promotes choice, competition and a dynamic market economy as the foundation for human dignity and progress. Reason produces rigorous, peer-reviewed research and directly engages the policy process, seeking strategies that emphasize cooperation, flexibility, local knowledge and results. Through practical and innovative approaches to complex problems, Reason seeks to change the way people think about issues, and promote policies that allow and encourage individuals and voluntary institutions to flourish.

Reason Foundation is a tax-exempt research and education organization as defined under IRS code 501(c)(3). Reason Foundation is supported by voluntary contributions from individuals, foundations and corporations. The views are those of the author, not necessarily those of Reason Foundation or its trustees.

Assessing the Social Costs and Benefits of Regulating Carbon Emissions

By Julian Morris

Executive Summary

U.S. government agencies are required to quantify the costs and benefits of regulations they propose. In the context of regulations pertaining to carbon emissions, the various agencies had been using differing (often implicit) estimates of the net social cost of carbon. In response, an Interagency Working Group was created in order to establish a consistent and objective "social cost of carbon" (SCC).

Although wide, the range of estimates of the social cost of carbon produced by the Interagency Working Group is both too narrow and almost certainly biased upwards. This is a consequence of using only three rather simplistic models, all of which use estimates of climate sensitivity that are likely too high and two of which likely overestimate the economic impact of climate change.

Taking into account a wider range of climate models, impact evaluations, economic forecasts and discount rates, as well as the most recent evidence on climate sensitivity, this study finds that the range of social cost of carbon should be revised downwards. At the low end, carbon emissions may have a net beneficial effect (i.e. carbon should be priced negatively), while even at the high end carbon emissions are very unlikely to be catastrophic.

Given this range of possible "damage functions," combined with significant uncertainty concerning the costs of limiting emissions of carbon dioxide and other greenhouse gases—costs which may, among other things, slow down the rate at which poor countries develop, thereby making the inhabitants of those countries more susceptible to climate and other changes—the social cost of carbon should be set at zero.

Table of Contents

Introduction and Outline of Study

Atmospheric concentrations of greenhouse gases (GHGs), which include carbon dioxide and methane, have been increasing for more than a century. Rising human emissions of these gases, especially from the combustion of fossil fuels and from agriculture, appear to be the primary cause of this increase in concentrations.

The temperature of the atmosphere has also increased over the past century. Some of that increase is likely the result of the increase in concentration of GHGs.[1] Such an increase in temperatures has various consequences, some of which are likely to be beneficial, others harmful.

In the late 1970s, economists began assessing the impact of rising greenhouse gas concentrations—and the consequences of restricting emissions. The framework they adopted for this analysis is called "cost benefit analysis." The objective of such analysis is to identify policies whose benefits exceed their costs.

In 1993, President Clinton signed Executive Order 12866 which, among other things, requires agencies of the U.S. government to "assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs."

Starting in 2008, in compliance with this executive order, some agencies of the U.S. government began to incorporate estimates of the "social cost of carbon" (SCC—see box) into their regulatory impact analyses (RIAs). However, not all agencies were using the same estimates of the social cost of carbon, resulting in regulatory impact analyses that were inconsistent. In response, the Office of Management and Budget and the Council of Economic Advisors convened an interagency working group in order to establish a consistent SCC for use in RIAs relating to regulations that restrict emissions of these gases.

The Social Cost of Carbon

"Social cost" is a term that has been used by economists to connote costs to society as a whole of an economic activity. It is usually used in contexts where social costs are believed to exceed private costs—and so are not adequately taken into account when individuals and organizations make decisions. In economics, "social cost" is equal to "private cost" plus "external cost" (where external cost is the monetary value of unaccounted for harmful effects). Thus, the "social cost of carbon" is the total cost to society arising from man-made emissions of carbon dioxide and other greenhouse gases. It is typically measured in U.S. dollars per metric ton of carbon dioxide or "carbon dioxide equivalent." ("Carbon dioxide equivalent" is used when assessing the many different gases that contribute to global warming and is an attempt to provide a single metric that accounts for the different levels of warming that result from different molecules.)

In February 2010, the Interagency Working Group (IWG) published "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866." In that document, a range of estimates was given for the SCC. Table 1 shows these estimates of the SCC for a metric ton of carbon dioxide given in "2007" U.S. dollars (to calculate the current dollar equivalents it would be necessary to increase them to account for the inflation since 2007). The SCC was calculated at five-year increments from 2010 to 2050 and, as Table 1 shows, it is expected to rise over time. As with all U.S. government estimates of costs and benefits, future costs and benefits are discounted (that is to say, future amounts are reduced by a certain percentage per annum to give their current dollar value). However, unusually, the IWG did not discount at the rate recommended by the Office of Management and Budget (7% per year), instead choosing to use a range of lower *and variable* discount rates (these averaged 2.5%, 3% and 5%). In addition, while most of the estimates provided are for the average (in this case, median) forecast of future costs and benefits, the IWG also gave an estimate of the "95th Percentile"—that is, the estimate that is above 95% of all forecasts, or in other words the estimate that is expected to occur with only 5% probability.

The IWG has revised its estimates three times since 2010. In the first revision (May 2013), the range of costs shifted upwards dramatically, as shown in Table 2. In the second revision (November 2013), the costs were revised downwards slightly compared to the May 2013 revision, as shown in Table 3. In the third revision (June 2015), the costs were again revised down slightly, as shown in Table 4.[2]

Table 1: Interagency Working Group Estimates of the Social Cost of CO_2 (in 2007 dollars)				
February 2010	**Average Discount Rate Assumed**			
	Median Forecast			**95th Percentile**
Year	**5%**	**3%**	**2.5%**	**3%**
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50	100
2035	11.2	36	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65	136.2

Source: Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," United States Government, February 2010.

Table 2: Interagency Working Group Estimates of the Social Cost of CO_2 (in 2007 dollars)				
May 2013	**Average Discount Rate Assumed**			
	Median Forecast			**95th Percentile**
Year	**5%**	**3%**	**2.5%**	**3%**
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

Source: Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," United States Government, May 2013.

Table 3: Interagency Working Group Estimates of the Social Cost of CO_2 (in 2007 dollars)				
November 2013	**Average Discount Rate Assumed**			
	Median Forecast			**95th Percentile**
Year	**5%**	**3%**	**2.5%**	**3%**
2010	11	32	51	89
2015	11	37	57	109
2020	12	43	64	128
2025	14	47	69	143
2030	16	52	75	159
2035	19	56	80	175
2040	21	61	86	191
2045	24	66	92	206
2050	26	71	97	220

Source: Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," United States Government, November 2013.

Table 4: Interagency Working Group Estimates of the Social Cost of CO_2 (in 2007 dollars)				
July 2015	Average Discount Rate Assumed			
	Median Forecast			95th Percentile
Year	5%	3%	2.5%	3%
2010	10	31	50	86
2015	11	36	56	105
2020	12	42	62	123
2025	14	46	68	138
2030	16	50	73	152
2035	18	55	78	168
2040	21	60	84	183
2045	23	64	89	197
2050	26	69	95	212

Source: Technical Support Document: Interagency Working Group on Social Cost of Carbon, "Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866" (revised July 2015), Washington, D.C., Environmental Protection Agency, p.3., https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf

This study seeks to assess the IWG's estimates of the social cost of carbon (SCC). It begins with a discussion of the framework that underpins the SCC, i.e. cost-benefit analysis. Part 2 provides a brief history of economists' attempts to estimate the social costs and benefits of carbon. Part 3 reviews some of the estimates of the social cost of carbon that have been derived using integrated assessment models (that is, the types of models used by the IWG). Part 4 describes the methodology adopted by the IWG for calculating the social cost of carbon and assesses some of the criticisms of that assessment. Part 5 focuses on two key factors affecting the "damage function": the sensitivity of the climate to increases in greenhouse gases and the ability of society to adapt to climate change. The final part draws conclusions based on analyses in previous sections.

Part 1

Cost-Benefit Analysis

Mainstream economists have tended to view the problem of climate change through the lens of cost-benefit analysis (CBA). The premise of CBA is that policies should be designed to achieve a "social optimum" by maximizing the discounted net benefits to society. So, for example, in Figure 1, net benefits, which are equal to "total benefits" minus "total costs," reach their maximum at an output of 15 units.

For cases in which the marginal (incremental) benefits decrease and the marginal (incremental) costs increase with rising output, the social optimum occurs at the point at which marginal social benefits are equal to marginal social costs, as shown in Figure 2.[3]

Figure 1: Total Benefits, Total Costs, Net Benefits and the Social Optimum

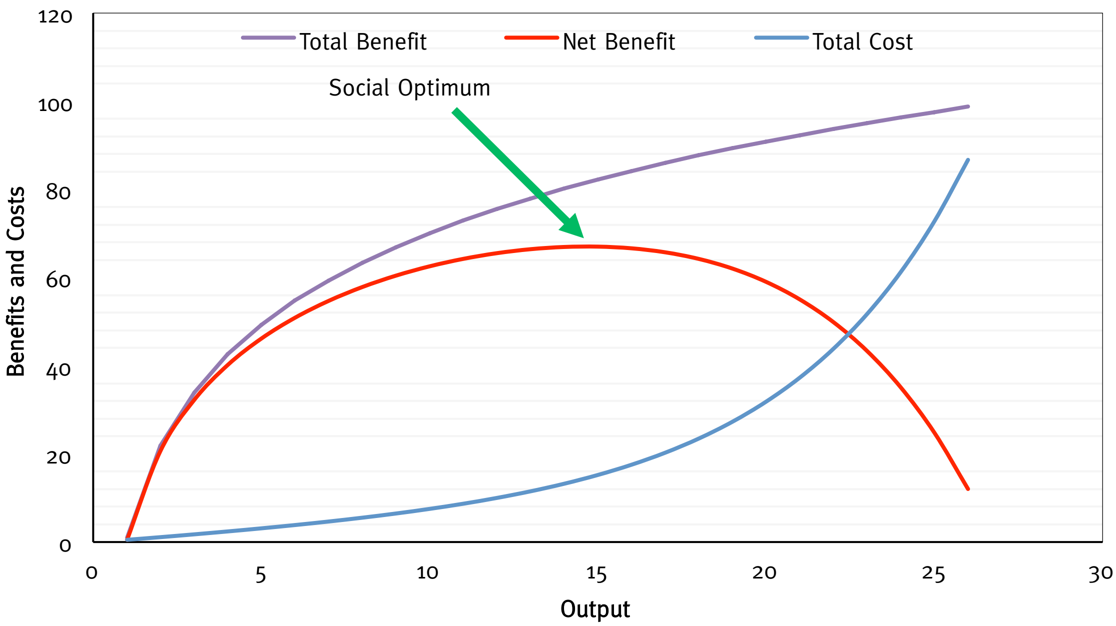
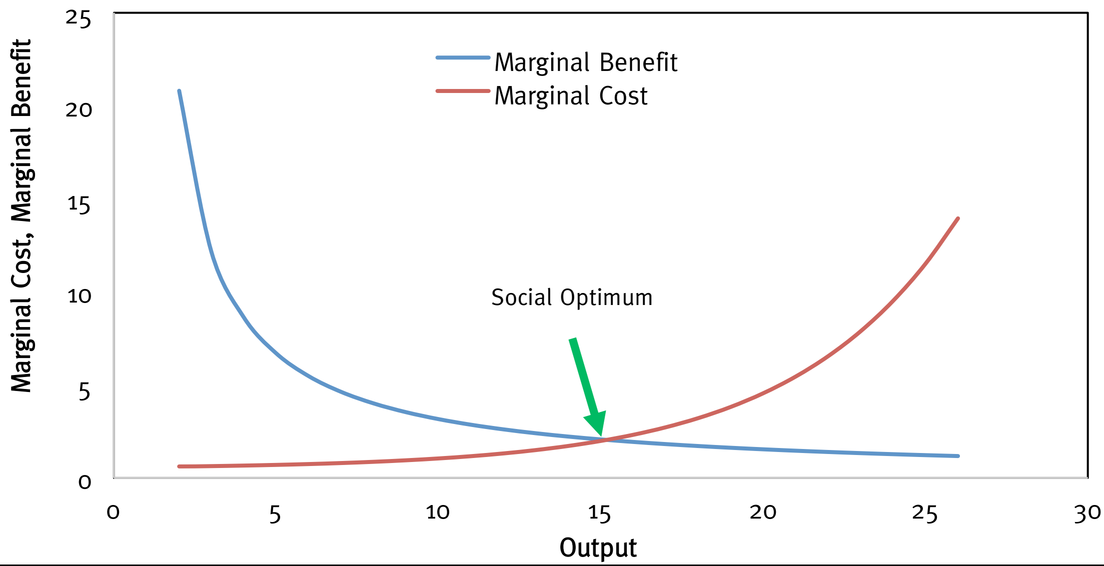


Figure 2: Marginal Social Benefit, Marginal Social Cost and the Social Optimum



There are numerous problems with cost-benefit analysis (CBA), not least of which are:

CBA inherently involves trading benefits to some people and costs to others.

Unless the beneficiaries of such policies actually compensate those who are harmed, policies based on CBAs will have distributional effects that may harm some individuals.

For example, consider a policy that reduces emissions of noxious substances from an industrial plant built next to a heavily populated neighborhood. Suppose that the policy significantly reduces the incidence of respiratory diseases among children and the elderly in the neighborhood; clearly these people benefit significantly. However, to achieve the reductions, the owners of the plant must increase expenditures on pollution abatement equipment, resulting in a reduction of investments in other areas and some layoffs of staff who live in the neighborhood of the plant. Even assuming that the policy is constructed in such a way as to maximize net benefits, some individuals will lose out.

Whether or not these distributional effects are deemed to be morally acceptable will depend on both the nature of the harm and the moral framework of those evaluating the policy. In the case above, consider two scenarios: in scenario one, the industrial plant was built in an open field, the neighborhood developed around the plant, and each new occupant knew in advance of their occupation the adverse effects of the plant's pollution. In scenario two, the plant was built in an existing neighborhood. In the first scenario, it could be argued that the harm from the noxious emissions was actually caused by the people who moved into the neighborhood—since the harm (to them) only exists because of *their* decision to move there. In the second scenario, the harm is clearly the result of the operation of the plant—it is a result of the actions of the plant owner. Under a moral framework in which the agents creating harm are required to compensate those who are harmed—which is the plain meaning of the "polluter pays principle"—the imposition of restrictions on the plant would be justified in the second scenario but not in the first.

CBAs seek to put monetary values on the effects of regulation.

To do so, they must make assumptions about the value individuals place on these effects. While some of the effects pertain to items that are traded in markets—and therefore have a known price—others are not traded in markets, so prices must be imputed. For example, a policy may have the effect of increasing the price of certain commodities and products made from those commodities that are traded in markets. A price (cost) can therefore be put on this effect, at least regarding the contemporary effect. At the same time, another effect of the policy might be to reduce health care expenditures by reducing the number of hospital visits, payments for medicines and so on, all of which are traded in markets. A price (benefit) can be put on this effect. However, other effects—such as health benefits to individuals—are not traded in the market: how does one put a price on an additional year of life, for example? Economists have sought to answer this question by using proxies, such as the implicit amount individuals are willing to accept in return for undertaking work that carries a higher probability of injury or death.[4] But while such proxies may be all that one has to go on, they are not real prices.

In addition to the challenge of actually making reliable inferences for one group of people on the basis of activities undertaken by another (as is the case with the proxy measures used to determine the "value" of non-traded benefits and costs), there remains the problem that such proxies are based on actions undertaken voluntarily, whereas by their nature, CBAs aim to assess the impact of regulations (and other public projects) that are imposed involuntarily. Since individuals tend to place a higher value on voluntary actions than on involuntary actions—and, conversely, feel a greater cost to actions imposed upon them—CBAs using proxies derived from voluntary decisions may overvalue the benefits and undervalue the costs of any regulatory decision.[5]

Any CBA must rely on forecasts of effects.

The above concerns demonstrate some of the difficulties and problems obtaining ballpark estimates of the likely short-term effects of the introduction of a specific regulation affecting one industry. Increasingly, CBAs are being used to evaluate the impact of regulations that have much longer term impacts. In such cases these difficulties and problems are magnified. For example, a CBA that seeks to evaluate the effects of a regulation 25 years hence will have to make assumptions concerning the technologies that will be available at that time in the future.

This is no mean feat: Imagine a regulator in 1990 seeking to undertake a CBA of a regulation that might restrict commercial use of the Internet. While hypertext transfer protocol (http—the protocol underpinning websites) was developed in 1989, the first website did not go online until 1991. Moreover, there were essentially no means of establishing secure transactions online (the secure sockets layer, https, was developed in 1995). So, the regulator would not even be able to *imagine* how online transactions might take place, let alone how many there might be or their value.

In addition to the difficulties of forecasting the existence, cost and impact of future technologies, all future costs and benefits must be discounted at an appropriate rate.

The main reasons for discounting are "opportunity cost" and "time preference." Opportunity cost refers to the fact that there are many potential investments and a choice must be made between these; specifically, the opportunity cost is the difference between the return on the proposed investment and that of the next best alternative. So, for example, if one investment would yield 5% per annum and another 4% per annum, the opportunity cost is 1%. "Time preference" refers to the preference for consumption now rather than consumption later. While a general phenomenon (it is nearly always better to have something sooner rather than later), it is perhaps most obvious *in extremis:* someone suffering dehydration will almost certainly prefer a pint of water now to a pint of water tomorrow, since without the pint now there may be no tomorrow. (Of course it is not *always* true: a person who is well hydrated today but plans to spend the next day running a marathon may well prefer the pint of water tomorrow.)

Unfortunately, there is no simple, single formula for calculating the appropriate discount rate. Not only is there variation in rates of return on investment over time and space, but individuals differ considerably in their time preference. Moreover, time preference varies according to socioeconomic status (poorer individuals have a higher time preference),[6] as the water example above indicates. We discuss this further in Part 4.

In the case of emissions of greenhouse gases, CBAs often seek to evaluate the effects of policies over many decades, even centuries.

Given the problems with attempting to forecast even a few years ahead, combined with the fact that the preferences of people who won't be born for many decades cannot be known, such evaluations need to be taken with a Siberian mine of salt.

Part 2

How Economists Have Sought to Estimate the Social Cost of Carbon

The earliest published estimate of the costs and benefits of carbon emissions is a 1977 paper by Yale University economist and then-member of President Carter's Council of Economic Advisors William Nordhaus.[7] That early paper offered a simple "optimization" model with three broad strategies to address the problem of carbon dioxide emissions:

1. *Nature's way and pray: do nothing*
2. *Reduce energy consumption*
3. *Reduce atmospheric concentrations*

Nordhaus then built a simple model that investigates the costs of achieving four cases:[8]

Case	Limit on increase of atmospheric carbon dioxide concentration
I: Uncontrolled Case	No limits (i.e. infinite)
II: Least Stringent Control Case	Limited to 200% increase over pre-industrial concentration
III: Base Control Case	Limited to 100% increase over pre-industrial concentration
IV: Most Stringent Control Case	Limited to 50% increase over pre-industrial concentration

Nordhaus describes the model he developed as "a linear programming model designed to simulate the functioning of a competitive market for energy products," which involves, "551 constraints and 2991 variables." That sounds complicated—and it was, especially considering the computing power available at the time. But considering the model was aiming to approximate the behavior of up to 10 billion people (Nordhaus's assumption for the peak human population in 2050), it is clearly a gross simplification.

The model estimated "shadow prices" for carbon dioxide (i.e. the price of carbon that, if applied to all emissions of the gas, would achieve the objective specified) at 20-year intervals from 1980 to 2160 for each of the four cases. In each case the shadow price begins low and gradually rises—as can be seen in Table 5. (Note: these are not precisely "social costs" because Nordhaus did not specify a damage function, so his results cannot be directly compared to later studies of social costs of carbon, which are optimized by using a damage function.)

Table 5: Nordhaus's Original Estimates of the "Shadow Price" of Carbon Dioxide in his 1977 Paper (in 1977 dollars)

	Program			
	I (Uncontrolled)	II (200% increase)	III (100% Increase)	IV (50% Increase)
1980	0.00	0.00	0.14	1.65
2000	0.00	0.07	1.02	12.90
2020	0.00	0.52	8.04	109.00
2040	0.00	4.07	67.90	123.60
2060	0.00	34.47	94.40	200.00
2080	0.00	42.00	94.40	200.00
2100	0.00	42.04	87.20	198.20
2120	0.00	41.91	87.10	198.50
2140	0.00	42.92	86.90	188.40
2160	0.00	40.93	95.10	95.10

Source: William D. Nordhaus, "Strategies for the Control of Carbon Dioxide," Cowles Foundation Discussion Paper, Yale University: Cowles Foundation, 1977, at p. 62.

As Nordhaus notes in his conclusion, "The central question for economists, climatologists, and other scientists remains: How costly are the projected changes in (or uncertainties about) the climate likely to be, and therefore to what level of control should we aspire."[9]

Two years later, Ralph d'Arge developed an optimization model that would become the standard for future analyses of the impact of climate change.[10] It is worth noting d'Arge's assessment:

> *In summary, there is substantive evidence of direct economic linkages between economic costs and different climates as represented by differences in mean annual temperature. In particular, colder climates will be more costly for agricultural production, forest production, and marine resources. Colder climates will also require more urban resources for sustenance, although there may be offsetting factors between heating and cooling requirements.*[11]

The emphasis on cooling is particularly striking. Between the 1940s and the 1970s, the climate had cooled and widespread predictions of continued cooling were being cited as reason for alarm.

D'Arge notes that most of his estimates of economic costs of climate change were "very crude" and carried out for only a single country (the United States). In the late 1980s, Nordhaus developed a new optimization model that sought more comprehensively to quantify both the costs of projected changes in climate and the cost of taking action to reduce emissions. The objective was to determine the *optimum reduction* in emissions of greenhouse gases—and the timing of that reduction. The first iteration of this model was published in 1989.[12] A second version was published in 1991. In that second paper, Nordhaus described what he was attempting to achieve:

> *In what follows, we will concentrate upon efficient strategies to reduce the costs of climate change. An efficient strategy is one that maximises overall net economic welfare (call it 'green GNP'), which includes all goods and services, whether or not they are metered by markets, and includes all externalities from economic activity.*[13]

While the resultant model is more complex (facilitated by the greater computational power available by the late 1980s), the central problem remained unchanged, as Nordhaus notes: “We have surveyed the economic literature on the costs and benefits of different policies. Estimates of both costs and damages are highly uncertain and incomplete, and our estimates are therefore highly tentative.”[14] To address this uncertainty, he considers three alternative damage functions: low, medium and high. And he concludes that for the low damage function the equilibrium marginal social cost of carbon is $1.83 per ton of CO_2 equivalent (CO_2e), for the medium damage function the SCC is $7.33/ton CO_2e (he does not supply an equilibrium SCC for the high damage function but notes that it entails a reduction in GHG emissions of “about one-third” from baseline.)[15]

Since these early efforts, dozens of economists have attempted to produce estimates of the social costs and benefits of carbon, resulting in an explosion in the literature on the issue. Most analyses use what have become known as “integrated assessment models” (IAMs), the basic methodology of which follows Nordhaus’s 1991 model and involves six steps:[16]

1. Develop (or choose from existing) scenarios of future emissions of GHGs
2. Use those scenarios to estimate future atmospheric concentrations of GHGs
3. Project changes in average global temperature and/or climate resulting from these future atmospheric GHG concentrations
4. Estimate the economic consequences of the resultant changes in temperature/climate
5. Estimate the costs of abating specific amounts of GHG emissions
6. Combine the estimates from steps 4 and 5 to produce an assessment of the net economic effect of different scenarios and thereby identify the optimum path of emissions.

While this may look simple on paper, each step is fraught with challenges, including:

1. Step 1 involves making assumptions about future population, economic growth and technological change, none of which are known.
2. Step 2 involves making assumptions regarding the various physical processes that affect release, breakdown and absorption of GHGs. While advances have been made in the understanding of these processes, significant uncertainties remain.

3. Step 3 involves modelling the extremely complex relationship between changes in atmospheric concentrations of GHGs, temperature and other climatic processes. The basic physics of the greenhouse effect is well established. However, the more complex feedbacks and interactions that determine how changes in GHG concentrations ultimately affect climate remain poorly understood.

4. Step 4 requires knowledge, first, of the relationships between climate change and various effects, ranging from agricultural productivity to human health to ecosystem function. Some analysis of these relationships has been undertaken but the results remain highly tentative and essentially descriptive. Attempts to make projections based on these analyses remain in the realm of conjecture. As William Nordhaus said in 1990, "If climate change itself is *terra infirma*, the social and economic impacts of such change are *terra incognita*."[17]

5. Step 5 is in some respects less challenging than step 4, at least for short-term projections, but huge uncertainties exist nonetheless. Even in the relatively short term, dramatic changes in the prices of various factors of production, such as of various sources of energy, can alter the outcome significantly (viz. the effects of the recent decline in the price of oil and natural gas). In the long term, unknown—and unknowable—changes in technology will largely determine the costs of taking action.

6. Step 6 requires the use of appropriate discount rates, exchange rates and other adjustments that translate the effects at different time periods on different people into a common metric. For example, most analyses make assumptions about the "welfare" effects of changes in consumption (they typically assume that wealthier people derive less welfare from additional consumption than poorer people). Such assumptions are in principle quite reasonable; the problem comes when attempting to assign specific numbers to these discount rates and welfare effects.

Part 3

Estimates of the Social Cost of Carbon Using Integrated Assessment Models

Given these challenges, it is perhaps not surprising that different IAMs, run using different emissions scenarios and other assumptions, have come up with widely differing estimates of the social cost of carbon.

In 2005, the United Kingdom's House of Lords Select Committee on Economic Affairs published an assessment of the economics of climate change. The Inquiry included an analysis using two IAMs: MERGE (developed by Professors Alan Manne, of Stanford University, and Richard Richels, of the Electric Power Research Institute) and FUND (developed by Professor Richard Tol, then at the University of Hamburg, Germany). The outputs of these IAMs are given in Table 6. As can be seen in the final two columns, these IAMs differ both in the "optimum" level of atmospheric GHGs—with MERGE indicating that the optimum is closer to 450 parts per million of carbon dioxide equivalent, while FUND indicates an optimum of closer to 550 ppm—and in the implied social cost, with FUND finding a social cost more than three times that of MERGE.

Table 6: Estimates of the Social Cost of Carbon from the House of Lords Study

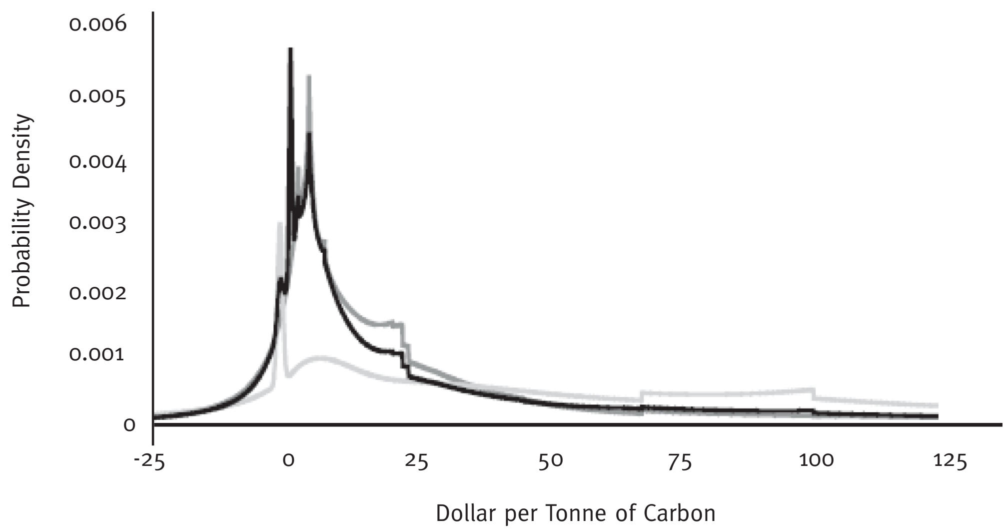
Concentration target (ppm)	Social cost per tC* in U.S. $2005	
	MERGE	FUND
750	-	-
650	18.3	79.8
550	18.3	44.4
450	13.1	59.3

Source: House of Lords Select Committee on Economic Affairs, 2005: http://www.publications.parliament.uk/pa/ld200506/ldselect/ldeconaf/12/1208.htm#a40

*tC = cost per metric ton of carbon dioxide equivalent.

Professor Tol, developer of the FUND model and now professor of economics at the University of Sussex, has undertaken a series of surveys of the literature on the social cost of carbon and developed meta-analyses of these costs. In a 2004 paper, he analyzed 103 estimates of the marginal damage costs of carbon dioxide from 28 published studies and found that the mode (the value that appears most often) was \$1.5/tC, the median (the middle value) was \$14/tC, the mean (the value obtained by summing all the values and dividing by the number of estimates) was \$93/tC.[18] The high mean value was a result of the fact that most of the distributions had long right tails and short left tails: while 5% of estimates found a SCC of -\$10/tC or less (implying that carbon dioxide emissions have significant net *benefits*), while at the other extreme 5% of estimates found a SCC of \$350/tC or more. This right-skewed distribution can be seen in Figure 3, which Tol describes as a "Composite probability density function, author weighted, for all studies (black), for all studies using equity weights (light gray, early peak, fat tail) and for all studies without equity weighting (dark gray, shallow tail)."

Figure 3: The Distribution of SCCs in Richard Tol's 2004 Meta-Analysis



Source: Tol, 2004 meta-analysis, Figure 4.

Since 2004, many other estimates of the social cost of carbon have been produced. One prominent example is included in a study of the economics of climate change commissioned by the then-Labour Government in the U.K. (in part, in response to the House of Lords report noted above). That study, known as the *Stern Review* after Nicholas Stern, the former development economist who oversaw its production, estimated the SCC at \$85/tC for the business-as-usual scenario (with a range from \$41 to \$124/tC).

It is worth noting, however, that Stern's analysis is an extreme outlier: it forecasts discounted losses from climate change in the absence of mitigation of between 5% and 25% of world GDP, while it asserts that the discounted cost of stabilizing greenhouse gases at 550 parts per million of CO_2e would be only about 1% of world GDP (with a range from -1% to 3.5%) in 2050.

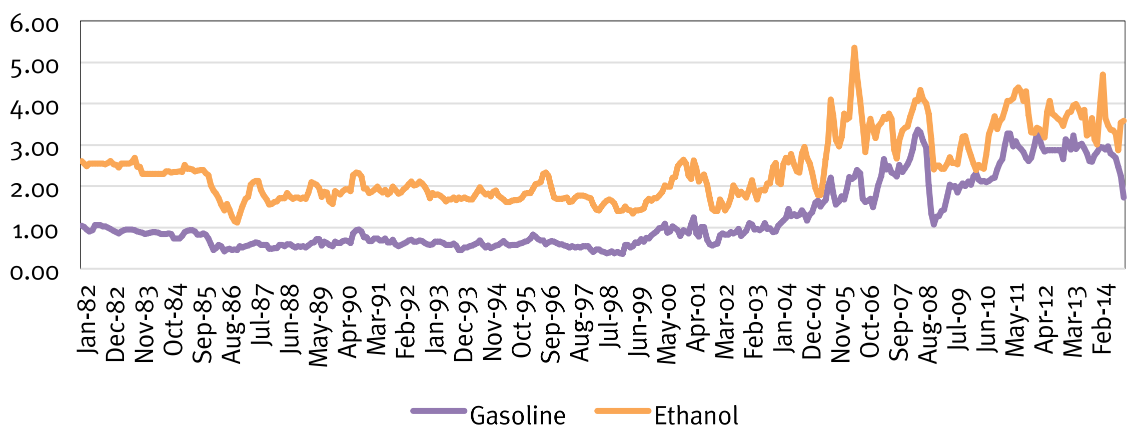
The *Stern Review*'s pessimism concerning the impact of climate change with unabated emissions arises from a combination of a long time horizon, pessimistic assumptions concerning the impact of rising temperatures on agriculture and other contributors to economic output in the far distant future, and the use of an extremely low discount rate.

Meanwhile, the *Stern Review*'s optimistic estimates of the costs of reducing greenhouse gas emissions result in part at least from optimistic assumptions regarding the costs of various carbon-reducing technologies. However, several of the *Stern Review*'s near-term assumptions have proved to be wide of the mark. For example, it assumed that the cost of ethanol as a fuel for vehicles would be lower than the cost of gasoline by 2015. Yet, as Figure 4 shows, the cost of a "gas equivalent" gallon of ethanol in the U.S. has consistently remained above that of gasoline for over 30 years. The *Review* also assumed that electricity produced using onshore wind generators would be only about 40% more expensive than electricity produced using the most cost-effective "fossil fuel option" by 2015. While this is in line with estimates of the levelized cost,[19] it fails to account for the intermittent nature of that energy source, which means that additional baseload power is required—at considerable capital and operating cost—to supply electricity when the wind turbine is idle.[20] It also fails to account for the costs of balancing the load on the network, as a result of highly variable power generation due to wind gusts, which means the amounts of other power supplied must be very rapidly increased or reduced.

It is not impossible that new technologies might be developed that enable significant reductions in carbon emissions at low or no cost. Indeed, as a study by scientists at the U.S. National Oceanic and Atmospheric Administration showed last year, emissions of carbon dioxide in the U.S. have fallen considerably over the past decade largely as a result of the switch to gas-fired electricity generation.[21] This fall in emissions has been driven by increased use of natural gas due to its greater abundance and lower cost, which in turn is the result of the widespread adoption of new technologies that have enabled lower-cost extraction of gas from shale deposits, combined with the introduction of new, more efficient, "combined cycle" generation technologies. However, the supposition that such technologies might have *negative* costs compared to what would happen in the absence of controls on carbon dioxide seems far-fetched; indeed, the only possible explanation for such an assumption is that the technologies would not have been developed *but for* those policies *and* that any negative impact of those policies is more than counterbalanced by the reduced cost of energy generated by the new technology.

In a 2008 update to his meta-analysis, Tol reviewed 211 estimates of the social costs of carbon and found that the estimates produced by the three dominant authors in the literature (Chris Hope, William Nordhaus and Tol himself) were significantly lower than the estimates by others, noting that "repeat contributors to the literature on the social cost of carbon are less pessimistic about the impact of climate change."[22] As regards Stern's social cost of carbon estimate, Tol notes that "Compared to the peer-reviewed literature, the Stern estimate lies beyond the 95th percentile—that is, it is an outlier."[23]

Figure 4: Cost of Ethanol and Gasoline in the U.S. 1982–2014, Current U.S. Dollars



Note: To enable direct comparison, the cost of ethanol has been adjusted to an amount per "gasoline equivalent gallons" to account for the lower energy density of ethanol compared with gasoline.

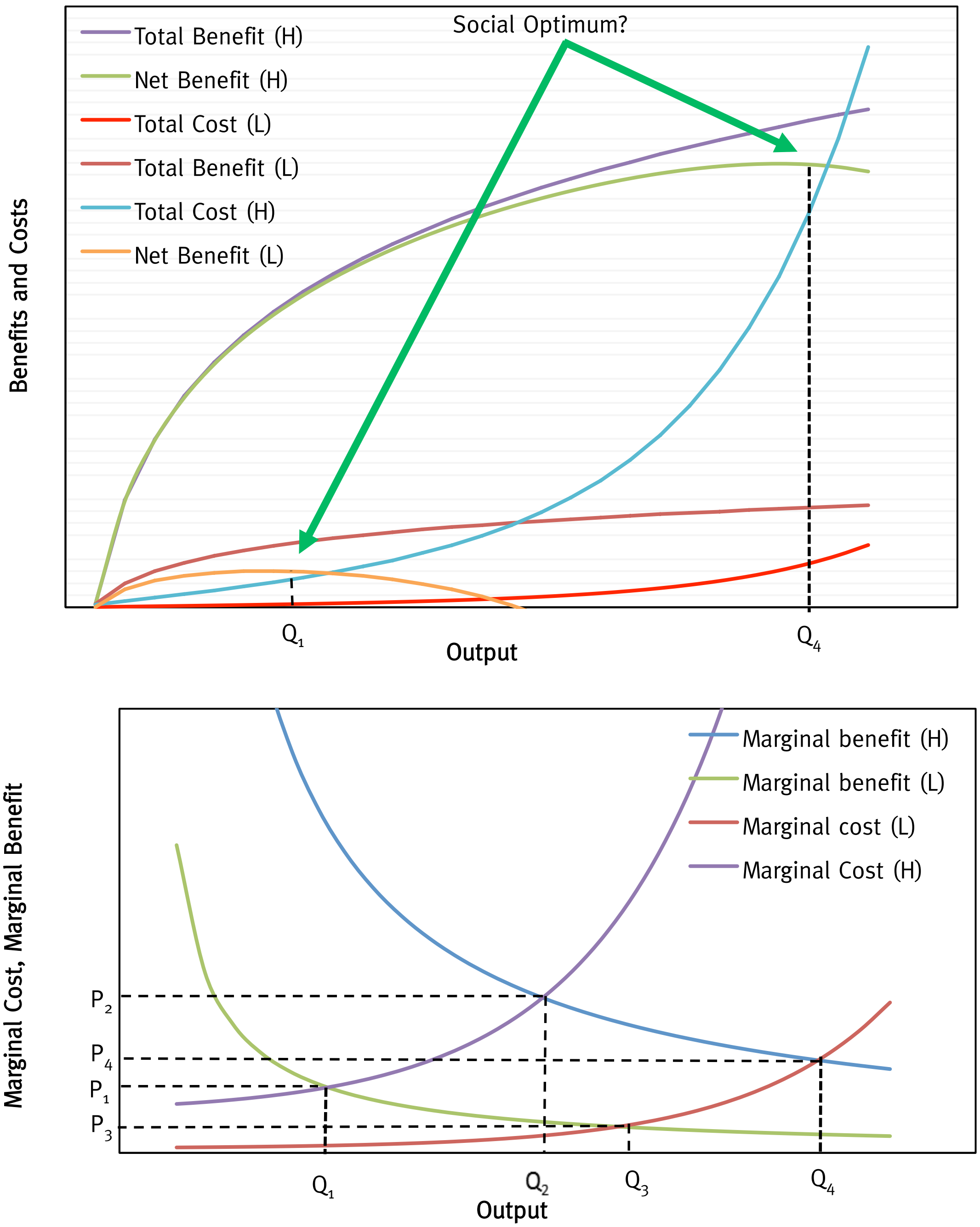
Source: U.S. Department of Agriculture: www.ers.usda.gov/.../US.../Prices/table14.xls

The *Stern Review*'s estimate of the SCC cannot be described as "incorrect," since the correct SCC cannot be known, but it is nonetheless outside the range of mainstream estimates. It is also rather implausible: the assumptions underpinning its estimates of both the damages from climate change and of the costs of taking action to reduce emissions of greenhouse gases, not to mention the (very low) discount rate chosen, seem unlikely. Indeed, the assumptions do not seem to have been made impartially; rather, they seem to have been chosen in such a way as to make more palatable certain political actions already being taken by the sponsors of the report (i.e. the British government).

Understanding the Problem with Estimating the Social Cost of Carbon

In broad terms, the problem with attempting to estimate the optimal social cost of carbon—given such a wide range of possible circumstances—is illustrated in Figures 5 and 6. These describe sets of hypothetical costs and benefits arising from human activities that result in carbon emissions. In each case, the SCC may be somewhere between the two marginal cost lines, (L) and (H). Meanwhile, the marginal social benefit of the output associated with different levels of carbon emissions may lie anywhere between the two marginal benefit lines (L) and (H).

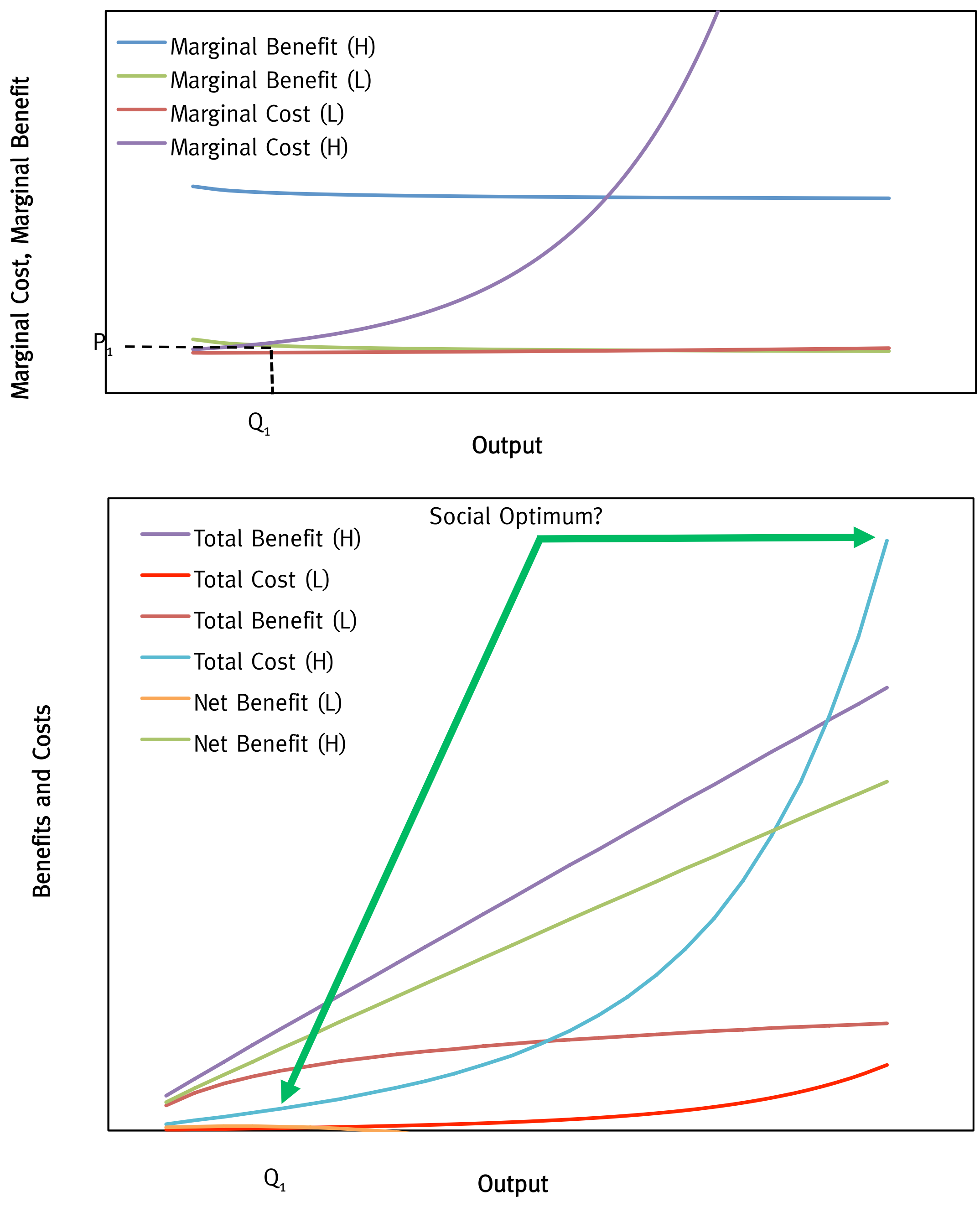
Figure 5: Hypothetical Marginal and Total Social Costs and Benefits of Carbon



So, depending on the shape of the marginal social benefit and marginal social cost curves, the socially optimum level of output might range anywhere from Q_1 to Q_4, while the optimal social cost of carbon ranges from P_3 (the intersection of the low benefit, low cost curve) to P_2 (the intersection of the high benefit, high cost curve).

But that's not the end of the story. As Figure 6 demonstrates, the range is potentially far wider, since it is possible that the marginal social benefits of carbon might always be higher than the marginal social cost, meaning that the optimal social cost of carbon might be negative.

Figure 6: Marginal and Total Social Costs and Benefits under Alternative Assumptions



One insight that emerges from reviewing these hypothetical social cost and benefit curves is that the optimal social cost of carbon (which, remember, occurs at the intersection of the marginal social cost and marginal social benefit curves) is highly dependent on the slope of the marginal social cost curve. If the effects of global warming are expected to be mild, then the marginal social cost curve might take the form of Marginal Cost (L) in Figure 6. By comparison, if the effects are likely to be harsh and rise dramatically with temperature, they might take the form of Marginal Cost (H).

Part 4

The Interagency Working Group's SCC

To calculate its initial (2010) estimates of the social cost of carbon, the Interagency Working Group (IWG) used three Integrated Assessment Models (IAMs):

- The Dynamic Integrated Climate-Economy (DICE) model developed by William Nordhaus and colleagues;[24]
- The Policy Analysis of the Greenhouse Effect (PAGE) model developed by Cambridge University economist Chris Hope and colleagues and;[25]
- The Climate Framework for Uncertainty Negotiation and Decision (FUND) model developed initially by Richard Tol and now co-developed by Tol and David Anthoff.[26]

The IWG ran these IAMs using five socioeconomic scenarios (IMAGE, MERGE Optmistic, Message, MiniCAM, 550 Average), with varying rates of growth of GDP, population and emissions. Depending on the scenario, world GDP in 2010 is assumed to vary from $45.9 trillion in the "MERGE Optimistic" scenario to $53.0 trillion in the IMAGE scenario, while GDP in 2100 ranges from $268 trillion in MERGE Optimistic (a 6-fold increase) to $396 in IMAGE (a 7.5-fold increase) (this is actually quite a narrow range: the 6-fold increase implies average annual growth of 2.0% over 90 years, whereas the 7-fold increase implies average annual growth of 2.2%). Meanwhile, population is assumed to increase from about 6.9 billion in 2010 to between 8.7 and 10.4 billion in 2100. Finally, emissions of carbon dioxide are assumed to change from around 30 gigatons/year in 2010 to between 12.8 gigatons (a reduction of nearly 60%) and 117.9 gigatons (an increase of around 300%) in 2100.[27]

While some of the projections (such as the assumed rate of economic growth) individually occupy narrow bands, the wide variation in emissions assumptions, combined with the differences in the structure of the models, generates widely differing estimates of the optimal social cost of carbon, as shown in Table 7.

Table 7: IWG Estimates of the Social Cost of CO_2 Disaggregated by Model, Socio-Economic Trajectory, and Discount Rate for 2010 (in 2007 dollars)

Model	Discount rate:	5%	3%	2.5%	3%
	Scenario	Avg	Avg	Avg	95th
DICE	IMAGE	10.8	35.8	54.2	70.8
	MERGE	7.5	22.0	31.6	42.1
	Message	9.8	29.8	43.5	58.6
	MiniCAM	8.6	28.8	44.4	57.9
	550 Average	8.2	24.9	37.4	50.8
PAGE	IMAGE	8.3	35.9	65.5	142.4
	MERGE	5.2	22.3	34.6	82.4
	Message	7.2	30.03	49.2	115.6
	MiniCAM	6.4	31.8	54.7	115.4
	550 Average	5.5	25.4	42.9	104.7
FUND	IMAGE	-1.3	8.2	19.3	39.7
	MERGE	-0.3	8.0	14.8	41.3
	Message	-1.9	3.6	8.8	32.1
	MiniCAM	-0.6	10.2	22.2	42.6
	550 Average	-2.7	-0.2	3.0	19.4

Source IWG TSD 2010, Table 3 (p. 26). http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf

A Conservative Estimate?

In producing its estimates of the SCC, the IWG adopted an approach that seems consistent with mainstream economic thinking about climate change. The IAMs it chose are the dominant ones in the literature (accounting for about three-quarters of the estimates reviewed in Tol's 2008 analysis).[28] Moreover, the central estimate of the SCC (which assumed a 3% discount rate) in the 2010 IWG analysis was \$21/tC, which is close to the \$23/tC of Tol's weighted estimate.

However, some critics of the IWG's SCC have claimed that it is *too conservative* in its approach. In a report for the Pew Foundation, Frank Ackerman and colleagues note that IAMs "do not embody the state of the art in economic theory and uncertainty, and the foundations of the economic component of the IAMs are much less solidly established than the general circulation models that represent our best current understanding of physical climate processes."[29] Ackerman et al. identify broadly three problems with IAMs:

1. The benefits of climate mitigation might be greater than the IWG asserts.

Ackerman et al. argue that "the benefits of mitigation are both unpredictable and unpriceable." It is difficult to disagree with that statement. They go on to point out that "IAMs are completely dependent on the shape of their assumed damage functions." That is also quite correct. But Ackerman et al. seem to have their own ideas regarding the shape of the damage function. For example, they challenge the assumption made in some IAMs that warming and carbon dioxide enrichment will lead to increases in agricultural productivity; in so doing, they cite selectively from the literature. Numerous studies published over the past two decades have shown higher levels of carbon dioxide (up to at least 700 ppm) would likely increase output of most of the world's main crops; recent analyses confirm these assessments for crops, including: soybeans,[30] wheat (and rye),[31] rice[32] and corn.[33]

Ackerman et al. then make much of the fact that most IAMs use mere quadratic functions, noting that the *Stern Review* team used a cubic function in a sensitivity analysis, which resulted in much more significant damage. Of course it would![34] But that doesn't make Stern's analysis better than any other IAM. (As Ivan Rudik recently demonstrated, a quartic function would result in even more extreme damage.[35]) If the shape of the damage function is unknown, then it is unknown. It could be flatter than any particular IAM assumes. It could be more curvaceous. It is impossible to know.

(In a similar vein to Ackerman et al., eminent Harvard economist Martin Weitzman has argued that the distribution of damages might have "fat tails," which would mean that the probability of catastrophe is higher than most economic models assume.[36] Weitzman then takes this hypothetical proposition and imputes an arbitrary probability distribution, which illustrates his case. Although Weitzman's argument has garnered much attention, it remains essentially hypothetical since his probability distribution has no basis in fact, so it is difficult to see what it adds to the conventional analysis.)

2. The costs of mitigation are overestimated.

Ackerman et al. assert that "We have good reason to believe that most IAMs overestimate the costs of achieving particular stabilization targets. Most IAMs exclude the possibility for 'no-regrets' options—investments that could reduce emissions without imposing significant opportunity costs."[37] They go on to assert that, "These options do exist, largely in the area of improved energy efficiency."[38]

While some reduction in emissions of carbon dioxide and other greenhouse gases is almost certainly possible at low or even negative cost in the short term—for example by eliminating perverse subsidies and tax breaks—it is highly unlikely that the scale of reductions available is in the same order of magnitude as the reductions that would be required to keep atmospheric concentrations of greenhouse gases from doubling by the end of the century. Thus, if such reductions are required, they will either come about as a result of the introduction of new technologies, or by limiting economic activity.

With regard to the development of new technologies, Ackerman et al. observe that "economic models have tended to underestimate the pace of technological change and to overestimate the cost of solutions to environmental problems."[39] It may well be that new technologies will be developed that enable—or simply result in—reduced emissions at a very low cost. What is much less clear is whether such technologies will be developed in response to emission reduction mandates, or whether they will be developed anyway—regardless of any restrictions being imposed. The recent shift in the U.S. from burning coal to burning gas, which has been responsible for most of the reduction in greenhouse gas emissions in this country, shows how new technologies developed primarily for commercial reasons—and with no carbon reduction objective in mind—can play a significant role. It is even possible that mandates to reduce emissions may lock us into a narrow technological path, as companies seek to develop and implement incremental ways to cut emissions, diverting investments away from new technologies, some of which might have greater potential to cut emissions.

Given these observations, the claim that the IAMs overestimate the costs of reducing greenhouse gas emission seems unjustified. The simple truth is that we do not know what the cost of such reductions would be.

3. Future welfare and consumption are inappropriately discounted.

IAMs typically seek to maximize (human) "welfare," which is assumed to be a function of future consumption discounted by the pure rate of time preference, ρ.[40] In most IAMs, ρ is assumed to be greater than zero on the grounds that all individuals—and hence society as a whole—prefer consumption today rather than consumption tomorrow. But Ackerman et al. assert that "Numerous economists and philosophers … have argued that weighing all generations equally and setting ρ equal to zero is the only ethically defensible practice."[41] While it is true that some economists and philosophers have argued that ρ should be zero, that does not make it "the only ethically defensible practice." There are good reasons people prefer consumption today to consumption tomorrow. To make the water example from earlier more concrete: Millions of people around the world currently lack ready access to clean drinking water and as a result suffer repeatedly from debilitating and often-deadly water-borne diseases. Those people would almost certainly be willing to forego some future consumption in order to have clean drinking water today. As such, it is by no means obvious that the rate of time preference should be set to zero.[42]

In order to calculate the current value of future costs and benefits, and thereby arrive at the optimal SCC, IAMs use the "Ramsey formula," which enables the discount rate to vary over time in proportion to rates of growth of income and consumption: when income and consumption grow faster, the discount rate will be higher; when they grow more slowly, the discount rate will be lower. This makes sense intuitively: the opportunity cost of a marginal unit of income or consumption (that is, the "cost" of foregoing some current income and consumption in order to receive more future income and consumption) today is higher when the growth rate is higher because higher growth implies higher future income and consumption, and if a person knows he will be richer in the future, he will give more weight to his current consumption. The Ramsey formula is given as the sum of the rate of time preference, ρ, and the rate of growth of consumption, g, between time t and the present weighted by the marginal elasticity of consumption, η.[43]

The Ramsey formula is also directly analogous to the discount rate applied to investments, which comprises the rate of time preference plus the opportunity cost of investment. Because of this, many economists argue that the market rates of interest offer a good proxy for the social discount rate.[44]

Ackerman et al. observe correctly that "With r greater than zero, distant-future outcomes take on reduced importance in economic calculations."[45] That of course is the point of discounting. But Ackerman et al. then come up with a way around such discounting, pointing out that if the damage from climate change is sufficiently great, g (the rate of growth of consumption) may be negative. In that case, depending on the size of ρ and η, r might even be negative; in other words, future consumption becomes more important than current consumption.

While it is possible to imagine scenarios in which climate change results in catastrophic damage in the future, it is impossible to assign a probability to such events. This, say Ackerman et al., means that the Ramsey formula no longer holds and instead simply requires the application of very low discount rates, on the grounds that "very high damages implies that future consumption may decrease."[46]

But is that the correct way to address the inability to assign probabilities to future catastrophic outcomes? It is possible to imagine all manner of potentially catastrophic events, including asteroid strikes, super-volcanoes, pandemic viruses, nuclear annihilation, bioterrorism, robot aggression, and so on.[47] If it makes sense to apply a very low discount rate to the damages consequent on climate change because of the potential for catastrophic damage, then it presumably makes sense to apply a similarly low rate to damages from these other possible catastrophes. If that were done, it might—following the logic of Ackerman et al.—be necessary to redirect all our activities toward preventing such catastrophes. That seems unreasonable.

Robert Pindyck draws a much simpler and more reasonable conclusion: "IAMs cannot tell us anything about catastrophic outcomes, and thus cannot provide meaningful estimates of the SCC."[48]

SCC Updated

In May 2013, the IWG updated its estimates of the SCC, using newer versions of the various IAMs. As a result, the SCC increased considerably, as can be seen in Table 2. And it revised the estimates again in November 2013, making very small reductions (in most cases of the order of $1/tC), as given in Table 3. The IWG's new central estimate of the SCC became $33 per metric ton and then $32.

Following the release of these 2013 revisions, the Environmental Defense Fund, the Natural Resources Defense Council (NRDC) and the Institute for Policy Integrity released a paper by Peter Howard called *Omitted Damages: What's Missing from the Social Cost of Carbon*.[49] In contrast to the fundamental critiques by Ackerman et al. and Pindyck, Howard merely asserts that the IWG's estimates exhibit "downward bias" as a result of the alleged omission of various negative consequences of climate change, ranging from health and agriculture to productivity and economic growth. Howard asserts that the new central estimate of the SCC should be considered instead a "lower bound."

SCC Overestimated?

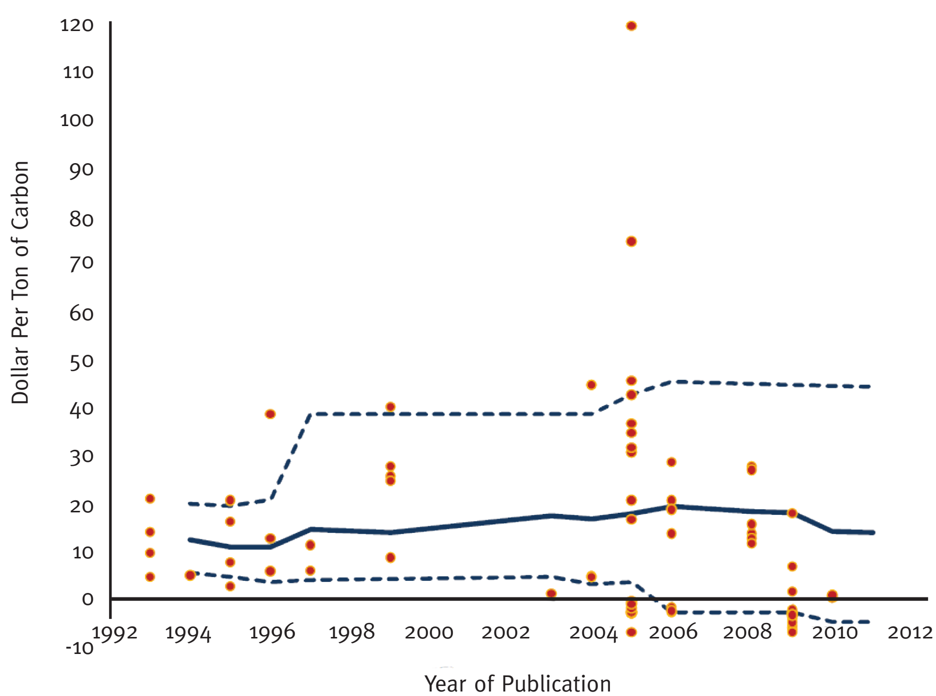
While some, such as Ackerman et al. and Howard, have criticized the IWG for underestimating the SCC, others argue that it overestimates the SCC. In a paper for the Federalist Society, former Administrator of the Office of Information and Regulatory Affairs Susan Dudley and former Associate Administrator for Policy, Economics and Innovation at the EPA Brian Mannix[50] observe that "the choice of discount rates … does not conform to the standard guidance issued by OMB, and is biased in the direction of low discount rates."[51]

The OMB guidelines state that for the base case, "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years."[52] William Nordhaus also favors the use of market interest rates and notes that in his empirical work, "based on returns from many studies, I generally use a benchmark real return on capital of around 6 percent per year."[53] While the IWG does provide an estimate of the SCC at a 5% discount rate, it is the *highest* rate given, with the clear implication that a lower rate is to be preferred.

In addition, Dudley and Mannix observe that while the IWG offers high-end estimates of the SCC, said to be based on the 95th percentile (i.e. the far tail of the distribution of estimates, such that 95% of estimates fall below that figure), it does not give corresponding low-end estimates such as for the 5th percentile (i.e. the figure above which 95% of estimates are to be found). Included in such a 5th percentile figure, say Dudley and Mannix, would be scenarios in which the earth cools, with negative consequences of various kinds. Under such circumstances, the SCC might be significantly negative, if the release of carbon dioxide would delay the harmful cooling.

In a 2011 update to his earlier meta-analyses of the social cost of climate, Richard Tol evaluated 311 estimates of the SCC.[54] Figure 7 reproduces Tol's figure from that paper showing "estimates of the social cost of carbon for a pure rate of time preference of 3%" by year of publication. Dots are individual estimates. The solid line is the mean and the dotted line is the 90% confidence interval of previously published studies.

Figure 7: Estimates of the Social Cost of Carbon, 1992–2011



Source: Richard Tol, *Social Cost of Carbon*, 2011, Figure 2.

Among the most interesting of Tol's findings in this update was that the mean SCC fell over time: for papers published before 1995, the SCC was estimated at $299/tC; for papers published between 1990 and 2001, it was $157/tC; for papers published after 2001, it was $113/tC. As Tol notes, "This suggests that estimates of the impact of climate change have become less dramatic over time."[55] Moreover, to the point Dudley and Mannix make regarding the inclusion of negative amounts for the SCC, as Figure 7 shows, even at a 3%

discount rate, many more recent studies find that the optimal SCC is less than zero—and the 90% confidence interval now crosses the x axis.

A very recent meta-analysis reviewed 809 estimates of the SCC from 101 studies. The analysis, conducted by an international team of economists with an expertise in meta-analysis (as opposed to climate economics), found evidence of publication bias in estimates of the SCC, resulting from the reluctance of peer-reviewed journals to publish estimates for which the 95% confidence limits include an SCC of zero.[56] The authors conclude that, "Our estimates of the mean reported SCC corrected for the selective reporting bias are imprecise and range between USD 0 and 130 per ton of carbon in 2010 prices for emission year 2015."[57] (The study has so far only been published online and not in a peer-reviewed journal, so the conclusions should be considered tentative.)

In a very recent paper, Stephanie Waldhoff, a research economist at the Joint Global Change Research Institute (a partnership between Pacific Northwest National Laboratory and the University of Maryland), David Anthoff, assistant professor of economics at the University of Berkeley and co-developer of the FUND model, Steven Rose, a senior research project manager at the Electric Power Research Institute (and formerly a senior economist at the EPA), and Richard Tol argue that the social cost of carbon dioxide may have been distorted relative to the social cost of other greenhouse gases due to the failure adequately to take into account the fertilization effect of carbon dioxide. When this effect is taken into account, the other greenhouse gases (specifically, methane, nitrous oxide and sulfur hexafluoride) become relatively more important.[58]

In a paper for the George Washington University Regulatory Studies Center, Brookings Institute Vice President Ted Gayer and Vanderbilt University Professor of Economics Kip Viscusi focus more narrowly on the legitimacy of the IWG's use of global benefits in its assessment of the SCC. Specifically, Gayer and Viscusi argue that the bases for evaluating the costs and benefits of regulations, including principally Executive Order 12866, Circular A-94 from the Office of Management and Budget, and Executive Order 13563, all call for assessments based on national, not global impact.[59] However, in its assessment of the SCC, the IWG chose to use global benefits, with the result that the benefits are overstated by at least four times (based on the U.S. share of global GDP) relative to what would have been the case had only national benefits been considered.

Part 5

The Damage Function

As already noted, for any IAM the "optimal" SCC is highly dependent upon the discount rate and damage function. The latter is, in turn, dependent on the assumed sensitivity of the climate to changes in atmospheric concentrations of GHGs and the degree to which society is able to adapt to any changes that occur. In this section, we consider these issues in more detail.

Climate Sensitivity

There are two measures of climate sensitivity: equilibrium climate sensitivity (ECS), which is the change in global mean surface temperature at equilibrium (that is, over the very long term—more than a century) in response to a doubling in the atmospheric concentration of CO_2; meanwhile, transient climate response (TCR) seeks to capture the shorter term (decadal to century) impact of a doubling in CO_2, and is usually taken to be the rise in global mean temperature in response to a continual increase in CO_2 concentrations of 1% per year for 70 years.[60]

In producing its original estimates of the SCC, the IWG cites the "Summary for Policymakers of the 2007 Report of the Intergovernmental Panel on Climate Change," which noted that equilibrium climate sensitivity "is likely to lie in the range 2°C to 4.5°C, with a most likely value of about 3°C." The IWG then notes that it consulted "with several lead authors" of the relevant chapter in the Intergovernmental Panel on Climate Change (IPCC) report and "selected four candidate probability distributions," which were then, "calibrated by applying these three constraints from the IPCC:

(1) a median equal to 3°C, to reflect the judgment of "a most likely value of about 3°C"

(2) two-thirds probability that the equilibrium climate sensitivity lies between 2 and 4.5°C; and

(3) zero probability that it is less than 0°C or greater than 10°C"[61]

It could be argued that, with the evidence available in 2010, this was a reasonable approach.[62]

One caveat: For the timescale of relevance to the IWG's analysis, the TCR is likely of greater importance than the ECS. All the IAMs incorporate a transient response, though they vary in the speed with which this response converges to the equilibrium, with MERGE converging more rapidly than FUND and PAGE. Which of these IAMs best reflects the actual transient response is unclear.

In 2008, several IAM modelers conducted an experiment in which they sought (among other things) to identify the impact of different model specifications on TCR.[63] For each model, atmospheric concentrations of CO_2 were assumed to grow by 1% per year for 70 years (and then stop, since that is the point at which concentrations would have doubled). The TCR—that is the temperature increase by year 70—varied from about 1.2°C for FUND to about 1.7°C for DICE.[64] Meanwhile, the ECS (reached after 150–300 years) ranged from about 2°C in PAGE to about 3°C in IMAGE. This ECS range is smaller than the ECS range assumed by the IWG, so (and assuming further that the same IAMs used by the IWG were calibrated for TCR in a similar way for the 2010 IWG runs as they were in the 2008 experiment) the TCR would have been somewhat higher in those IWG model runs than in that 2008 experiment—given the distribution of the ECS assumed by the IWG. In other words, even relative to what might have been considered best practice in 2010, the IWG seems to have adopted an ECS and, consequently, a TCR that was on the high side, which in turn will have resulted in an upward bias in estimates of the SCC.

Given the importance of climate sensitivity as a determinant of damage, it would be useful to know whether the assumptions of ECS and TCR used in the IWG's IAMs were accurate. In the past decade, several analyses have shown that the forecasts of future climate change underpinning the IPCC's various reports are upwardly biased:

- In a paper published in Nature Climate Change in September 2013, John Fyfe, Nathan Gillett and Francis Zwiers compared global mean temperature data (from the Hadley dataset) for the 20-year period 1993–2012 with 117 simulations produced by a group of 37 models that form the basis of the IPCC assessments, called the Coupled Model Intercomparison Project (CMIP5).[65] Fyfe et al. found that whereas the global mean temperature had risen by 0.14 ± 0.06°C, the models forecast an increase of 0.30 ±0.02°C (in each case the upper and lower bounds give 95% confidence limits). In other words, from 1993 to 2012 the world warmed at about half the rate the models forecast.
- In evidence submitted to the EPA, Professor John Christy compares a set of model runs from the same project (CMIP5) run over the period 1979–2014 and compares these with data from radiosondes and satellites.[66] As with the Fyfe et al. analysis,

Christie finds that the temperature trend of the models is significantly higher than that of the observations.

- In a paper published in *Geophysical Research Letters* in 2013, Kyle Swanson compares both older generation CMIP3 model ensembles and more recent CMIP5 ensembles with observed trends at various latitudes for the period 2002 to 2011.[67] Swanson concludes that while the earlier generation of models had sufficient internal variability to account for the changes that occurred, the narrower variability of the new models highlights an apparent upward bias.

While there are many possible explanations for this divergence between the forecast and observed global mean temperature, the use of inappropriate parameters for climate sensitivity is a prime candidate. This seems to have been confirmed by a series of empirical investigations of the ECS and TCR published since 2011, which suggest that both are considerably lower than was previously assumed.[68]

The biggest problem in estimating climate sensitivity from instrumental data is uncertainty regarding the cooling influence of aerosols, and hence about the extent to which warming attributable to greenhouse gases exceeds the global warming actually experienced. Another major challenge in establishing an empirically sound estimate of climate sensitivity is the noise in the data over interannual to multidecadal periods: there are simply so many different factors affecting climate that isolating the effects of an increase in carbon dioxide concentrations has necessitated both careful investigatory work to identify periods over which noise does not significantly distort the data used and careful statistical analysis to ensure that the estimates obtained accurately reflect the data used and the uncertainties involved. In most cases, the bounds of estimates remain wide. But, crucially, both the median estimates and the upper bounds of the majority of recent studies that satisfactorily address the foregoing problems are considerably lower than assumed in the IWG report.[69] This was acknowledged by Working Group One of the IPCC in its *Fifth Assessment Report* (AR5 WG1), published in September 2013, which discussed several of these more recent assessments and changed the range it gave for the ECS. In its "Summary for Policymakers," the IPCC asserted that "Equilibrium climate sensitivity is *likely* in the range 1.5°C to 4.5°C."[70] It also specifically notes that it has lowered the bottom end from 2°C to 1.5°C. And it removed mention of a median or best estimate.

With this new information, it should have been possible for the IWG to have adjusted the ECS underpinning its revised estimate in November 2013. Given the lower bottom end in the IPCC report, one would expect this to have *reduced* the likely temperature response and, hence, the damages. However, it does not appear that the IWG took this action.

Since the publication of the IPCC report, further studies have confirmed the upward bias in the ECS and TCR used in the IWG model runs.

As noted, one of the main contributors to noise in the temperature signal is aerosols, which reflect incoming solar radiation and may also make clouds brighter and/or longer–lived, and thereby cool the climate. One source of such aerosols is the sulphur dioxide that is emitted during the combustion of coal and other fossil fuels: these emissions are converted into sulfuric acid, which condenses to form aerosols. Aerosols also result from intentional and unintentional burning of trees and other biomass, as well as from other natural sources, such as volcanoes. But the scale and effects of these emissions are very difficult to estimate.

In a seminal paper recently published in *Climate Dynamics*, climate scientists Nicholas Lewis and Judith Curry address these problems by using periods relatively unaffected by volcanic activity and well-matched in terms of noise. Using this methodology and the estimated ranges for the cooling or warming forces of, inter alia, aerosols and greenhouse gases given in the IPCC AR5 WG1 report, they report a median estimate for ECS of 1.64°C, which is about 40% lower than the IWG's assumption of 3°C.[71]

If the ECS is 40% less than the IWG assumptions, then the damages predicted by the IWG are likely substantially upwardly biased. Importantly, the Lewis and Curry study and other recent studies with modest best estimates for ECS also place much tighter upper bounds on ECS than do earlier studies. Since damages are assumed to be non-linear in the models used by the IWG (as noted above, they are assumed to increase at a rate proportional to the square, or higher power, of the temperature increase), a 40% reduction in the ECS best estimate accompanied by comparable or larger reductions in the upper uncertainty bounds implies that damages might come down by an even greater extent. (The precise relationship depends on the model specification.)

But the ECS may be even lower. As explained, a main reason for the wide range of estimates of the ECS and TCR historically has been uncertainty regarding the impact of aerosols. But a paper by Bjorn Stevens of the Max Planck Institute for Meteorology published this year in the *Journal of Climate*, seems to narrow the bounds considerably. Specifically, Stevens finds that the maximum reduction in temperature caused by aerosols is considerably less than was assumed by the IPCC—and hence by Lewis and Curry. Armed with Stevens's new estimates of the impact of aerosols, Nicholas Lewis re-ran his analysis of ECS and TCR and found that the best estimate for ECS is 1.45°C.[72] Moreover, Lewis gives a 95% confidence interval for ECS of 1.05°C to 2.2°C. Meanwhile, Lewis provides a revised TCR best estimate of 1.21°C, with a 95% confidence interval of 0.9° to 1.65°C. If Stevens's and Lewis's analyses are both correct, then the IWG's models are off by more than 50%—and the upper bound is lower than the median estimate!

Technological Change, Adaptive Capacity and the Damage Function

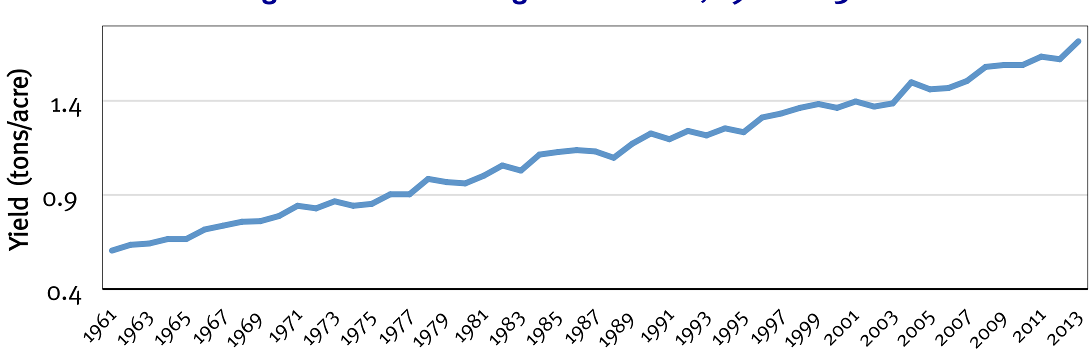
The impact of climate change is highly dependent on how humans respond to that change—in particular their "adaptive capacity," which is the degree to which humans are able to adapt by developing and adopting new technologies. Of the three IAMs used by the IWG, PAGE and DICE presume that adaptive capacity remains constant, whereas FUND assumes that adaptive capacity increases over time.

These and other differences in assumptions regarding adaptive capacity have a significant impact on the models' damage functions. In PAGE and DICE, all increases in temperature have net negative impacts on humanity. By contrast, in FUND increases in global mean temperature up to nearly 3°C have net benefits to society.[73] (These benefits arise largely from increases in agricultural output but also from reduced heating costs, which in combination more than offset the negative effects of climate change.)

So, which model is more plausible? All the models presume that there will be technological innovation; that is a pre-requisite for economic growth. While we cannot know precisely what new technologies will be developed in the future, it seems bizarre to assume that none of the innovation that is expected to take place will result in enhanced adaptive capacity. Historically, there has been a strong relationship between general innovation and increases in adaptive capacity. In the past century, innovative goods and services have dramatically reduced human exposure to climate-related risks, ranging from crop failure to deaths from extreme weather events. To give a few examples:

Increased agricultural yields. Over the course of the past half century, new agricultural technologies of various kinds (including crop cultivars, fertilizer, pesticides, water delivery systems, as well as tilling, planting and harvesting machines) have been developed and increasingly widely adopted. These have contributed to a near three-fold increase in average cereal yields, from around 0.6 tons/acre in 1961 to about 1.7 tons/acre in 2013, as shown in Figure 8.

Figure 8: World Average Cereal Yield, 1961–2013

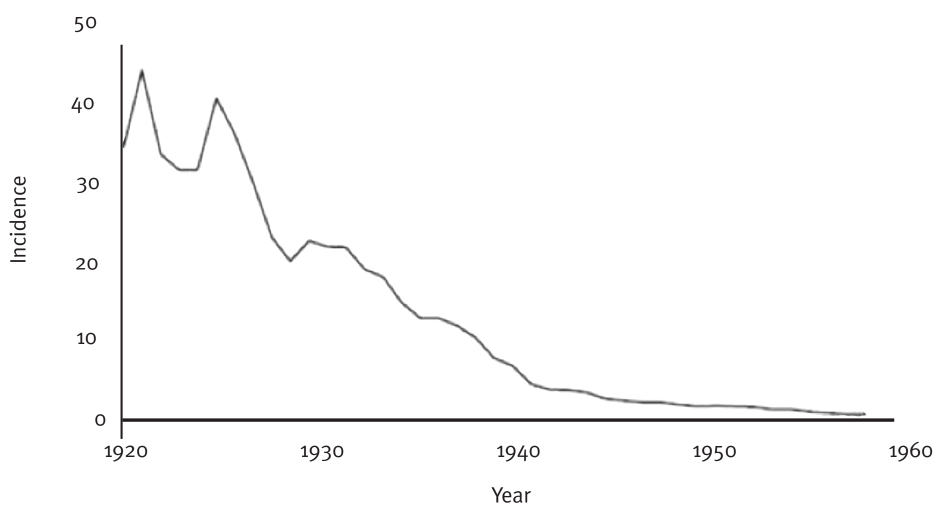


Source: FAOSTAT (www.faostat.fao.org).

Air conditioning. More efficient and cost-effective cooling systems, especially air conditioning, have dramatically reduced heat-related harm to human health. For example, in a 2014 paper published in the *Journal of Environmental Health Perspectives*, Jennifer Bobb et al. found that the death rate in the U.S. during heat waves (a 10°F (5.5°C) increase in same-day temperature) fell from 50 per 1,000 deaths in 1987 to 19 per 1,000 deaths in 2005 in part as a result of increased adoption of central air conditioning.[74] (The authors note that other factors, such as better treatment for heart attacks and other ailments associated with heatwaves, also likely played a significant role.)

Water purification. The development and adoption of better water purification systems have helped to prevent a range of water-borne diseases, including diarrhea, cholera and typhoid, that tend to be worse during hot weather. Figure 9 shows the decline in typhoid fever in the United States between 1920 and 1960—a direct result of improvements in sanitation and the availability of clean water.

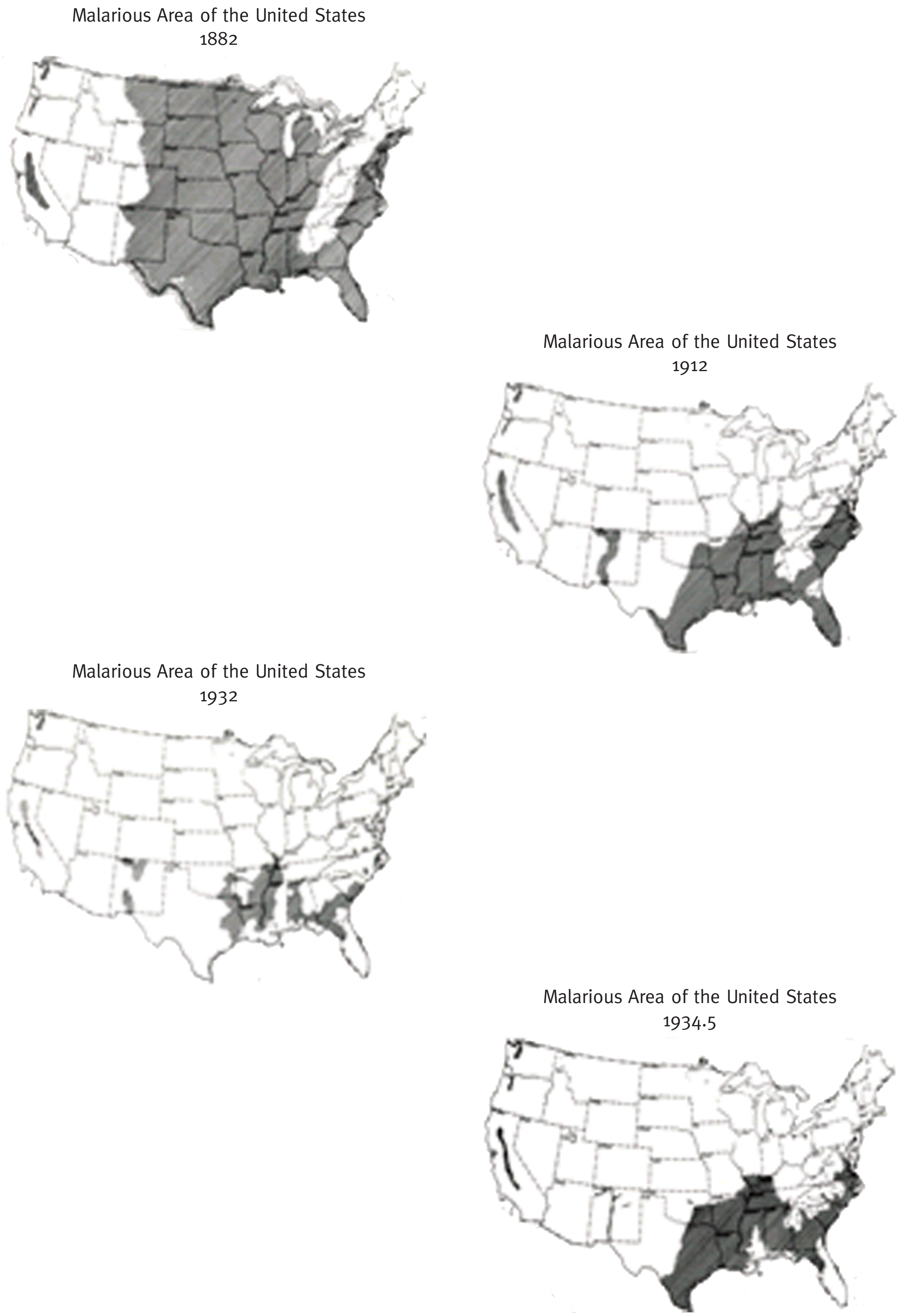
Figure 9: Decline in Typhoid Fever in the United States, 1920–1960



Source: Centers for Disease Control and Prevention

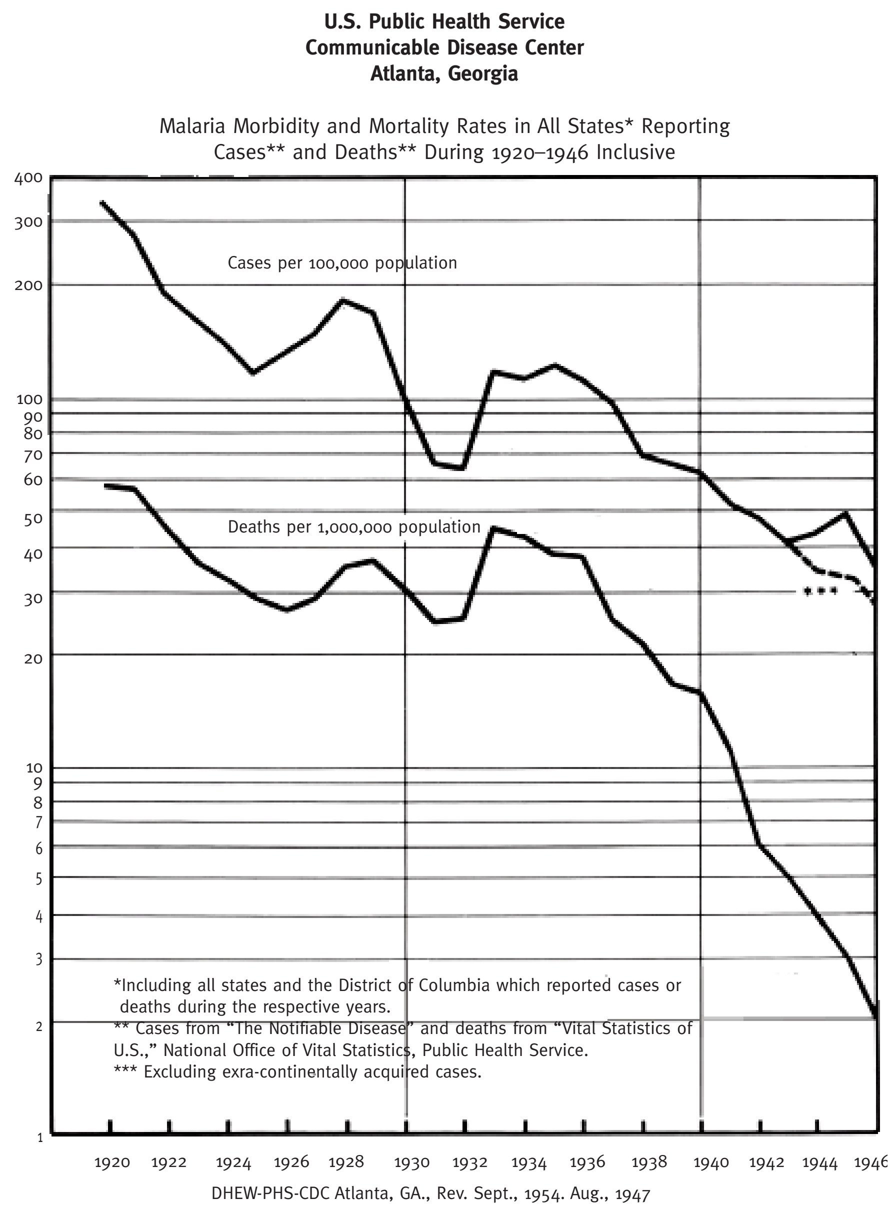
Prevention of vector-borne diseases. A combination of better livestock management, stricter separation of humans and animals, prevention and removal of stagnant water, effective use of insecticides, and the development and use of chemical prophylaxis has eliminated malaria from Europe and the U.S., where it was once widespread (see Figures 10 and 11). An analysis by Tol and Dowlatabadi suggests that malaria is functionally eliminated in all countries with an average per capita income of $3,100 and above.[75]

Figure 10: Malarious Area of the United States, 1882–1934



Source: Centers for Disease Control and Prevention:
http://www.cdc.gov/malaria/about/history/elimination_us.html

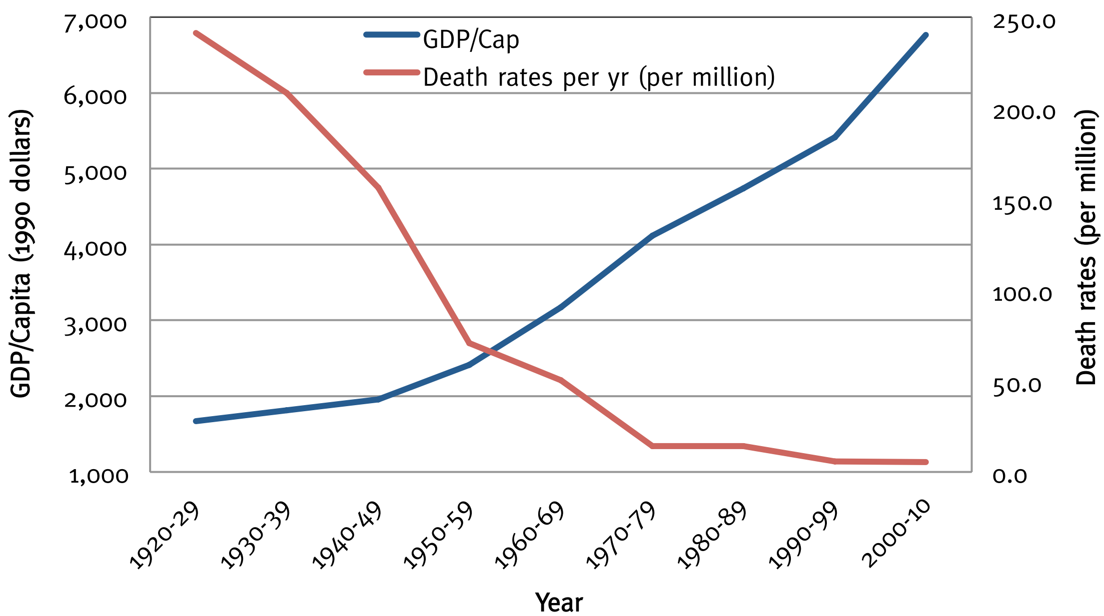
Figure 11: Malaria Morbidity and Mortality in the U.S. 1920–1946



Source: Centers for Disease Control and Prevention:
http://www.cdc.gov/malaria/about/history/elimination_us.html

Reduction in deaths from extreme weather events. Improvements in the production and distribution of food, better buildings (and building codes), early warning systems and other technologies have dramatically reduced mortality from extreme weather events, as shown in Figure 12. Indeed, over the past 100 years, the mortality from extreme weather events has declined precipitously. As Figure 12 shows, this decline has coincided with a dramatic increase in average income per capita.

Figure 12: Mortality from Exreme Weather Events (Average GDP/Capita)



Sources: EM-DAT (Deaths), Angus Maddison project (GDP, population), author's calculations.

The association between increased income per capita and reduced mortality from weather-related natural disasters is no mere coincidence. Increases in income are driven in large part by technological advancements that result in more-efficient and -effective goods and services.

Given that new technologies tend to make people less susceptible to all manner of climate-related phenomena and given that it seems most likely that such technological improvements will continue well into the future, it takes a rather high degree of pessimism to assume that adaptive capacity will not increase over time and, implicitly, that humans will not adapt quickly and relatively painlessly to a changing climate. Indeed, there is something of a contradiction in many of the more pessimistic assessments of future climate change: these tend to assume on the one hand that economic growth will occur at a rapid pace, which (in part at least) explains the increase in emissions of carbon dioxide. On the other hand, they assume that adaptation will be slow and expensive. Yet, if past economic growth has resulted from technological innovations that have generated enhancements in adaptive capacity, it seems illogical to presume that the innovations driving future economic growth won't also result in similar enhancements, so that in the future people will adapt more quickly and thus be less—not more—susceptible to all manner of climate-related problems.

As if to confirm the continuation of such trends, in just the past few years new crop varieties have been developed that offer the potential to increase production in more extreme environments. For example, the Drought Tolerant Maize for Africa project has developed 153 new varieties of drought tolerant maize (corn) that have the potential—now—dramatically to increase yields and reduce poverty throughout Africa.[76]

Part 6

Conclusion

This study began with a discussion of the methodology underpinning the "social cost of carbon," namely cost-benefit analysis. Several problems with this methodology were identified, including difficulties identifying the value of items that are not traded in markets and concerns regarding the moral implications of trading benefits accruing to one person against costs imposed on another.

These problems notwithstanding, in 2010, the U.S. government Interagency Working Group (IWG) made a valiant attempt to estimate the social cost of carbon. Unfortunately, the IWG based its estimates on assumptions that have turned out to be deeply flawed. In spite of producing two subsequent updates, the IWG has failed to change those assumptions in light of new evidence that indicates that it overestimated the damages that might result from climate change in its original report. To the contrary, the 2013 and 2015 updates were predicated on assumptions that the IWG had previously *underestimated* those damages.

What can we conclude about the social cost of carbon? First, over time, estimates of the mean social cost of carbon have been declining. But those estimates were predicated on assumptions about the equilibrium climate sensitivity that is likely overestimated by 40% or more. It seems reasonable to conclude that future estimates of the SCC that incorporate more accurate estimates of the ECS and TCR will fall commensurately.

Second, the pessimistic assumptions concerning humanity's future adaptive capacity, and hence the speed with which it will adapt to climate change, that are built into two of the three IAMs used by the IWG are ill-founded. If less pessimistic assumptions were made, the SCC would likely fall further.

Third, over time an increasing proportion of estimates of the SCC have included zero in their 95% confidence limits. If standard statistical analysis were applied to those estimates, the null hypothesis that the SCC = 0 could not be rejected.

Taking into account all these factors and based on all the evidence presented in this paper, it seems reasonable to conclude that the best estimate of the SCC is zero. Thus, policies and regulations that are predicated on the assumption that the SCC is different from zero should be adjusted to reflect an SCC of zero.

About the Author

Julian Morris is vice president of research at Reason Foundation.

Julian graduated from Edinburgh University in 1992 with an MA in economics. He has an MSc in environment and resource economics from University College London, an MPhil in land economics from Cambridge University, and a law degree from the University of Westminster.

Julian's undergraduate thesis examined the costs of controlling carbon dioxide emissions and he has continued to research and write on the economics of climate change ever since, including co-authoring *Global Warming: Apocalypse or Hot Air* (IEA, 1994) and editing *Climate Change: Challenging the Conventional Wisdom* (IEA, 1997) and the *Civil Society Report on Climate Change* (International Policy Press, 2007). Julian is the author of dozens of scholarly articles on the relationship between institutions, development and environmental protection, and the editor of several books, including *Sustainable Development: Promoting Progress or Perpetuating Poverty* (Profile Books, 2002).

Prior to joining Reason, Julian was executive director of International Policy Network, which he co-founded. Before that, he ran the environment and technology programme at the Institute of Economic Affairs.

Endnotes

1 This is a consequence of what is known as the “greenhouse effect”: certain gases (including water vapor, carbon dioxide and methane) slow down the rate at which incoming energy from the sun is radiated back into space, resulting in an increase in the temperature of the atmosphere, oceans and soil.

2 Technical Support Document: Interagency Working Group on Social Cost of Carbon, “Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866” (revised July 2015), Washington, D.C., Environmental Protection Agency, p.3., https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf

3 In mathematical terms, the result is derived as follows: (NET BENEFIT) = (TOTAL BENEFIT) – (TOTAL COST), thus (CHANGE IN NET BENEFIT WITH RESPECT TO OUTPUT) = (CHANGE IN TOTAL BENEFIT WITH RESPECT TO OUTPUT) – (CHANGE IN TOTAL COST WITH RESPECT TO OUTPUT). Since the optimum occurs at a point where the change in net benefit is zero, we can say that at this optimum: 0 = (CHANGE IN TOTAL BENEFIT WITH RESPECT TO OUTPUT) – (CHANGE IN TOTAL COST WITH RESPECT TO OUTPUT). Rearranging gives us, at the social optimum: (CHANGE IN TOTAL BENEFIT WITH RESPECT TO OUTPUT) = (CHANGE IN TOTAL COST WITH RESPECT TO OUTPUT). QED.

Rewriting in conventional economic jargon gives us:

MARGINAL BENEFIT = MARGINAL COST.

4 See e.g. the Environmental Protection Agency’s guide to “mortality risk valuation,” available here: http://yosemite.epa.gov/EE%5Cepa%5Ceed.nsf/webpages/MortalityRiskValuation.html , and its white paper here: http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0563-1.pdf/$file/EE-0563-1.pdf

5 Chauncey Starr “Social benefit versus technological risk,” *Science* 165 (3899), pp. 1232–1238, 1969; See also Baruch Fischhoff, Paul Slovic, Sarah Lichtenstein, Stephen Read and Barbara Combs, “How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits,” *Policy Sciences*, Vol. 9(8), pp. 127–152, 1978. This difference in valuation is likely due to differences in the cognitive processing of voluntary versus involuntary risk: Hengyi Rao, Marc Korczykowski, John Pluta, Angela Hoang and John A. Detre, “Neural correlates of voluntary and involuntary risk taking in the human brain: An fMRI Study of the Balloon Analog Risk Task (BART),”*NeuroImage* Vol. 42, pp. 902–910, 2008.

6 V. Griskevicius, J. M. Tybur, A. W. Delton and T. E. Robertson, “The influence of mortality and socioeconomic status on preferences for risk and delayed rewards: A life history theory approach,” *Journal of Personality and Social Psychology,* Vol. 100 (6), 2011, 1015–1026.

7 William D. Nordhaus, “Strategies for the Control of Carbon Dioxide,” Cowles Foundation Discussion Paper, Yale University: Cowles Foundation, 1977.

8 Ibid.

9 Ibid.

10 http://economicsofclimate.blogspot.co.uk/2015/01/origins-of-climate-economics-darge-1979.html

11 Ralph C. d'Arge, "Climate and Economic Activity," in Proceedings of the World Climate Conference, Geneva, 12–23 February 1979, pp. 661–679, Geneva, Switzerland: World Meteorological Organization, WMO paper No. 537.

12 William D. Nordhaus, "The Economics of the Greenhouse Effect." paper prepared for the 1989 meetings of the International Energy Workshop and the MIT Symposium on Environment and Energy, 1989.

13 William D. Nordhaus, "To Slow or Not to Slow: The Economics of the Greenhouse Effect," *The Economic Journal*, vol. 101, No. 407, July 1991, pp. 920–937.

14 Ibid. at p. 936.

15 Ibid.

16 These are similar to the six elements identified in Robert Pindyck, "Climate Change Policy: What do the Models Tell Us?" *Journal of Economic Literature,* 2013, Vol. 51(3) pp. 860–872.

17 William D. Nordhaus, "Greenhouse Economics: Count before you leap," *The Economist*, July 7, 1990.

18 Richard S.J. Tol, "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties," *Energy Policy*, vol. 33 (2005), pp. 2064–2074, published online June 5, 2004, hereinafter "Tol, 2004 meta-analysis," at p. 2071, Table 3. Available at: http://www.fnu.zmaw.de/fileadmin/fnu-files/publication/tol/enpolmargcost.pdf

19 See *Levelized cost of New Generating Technologies*, (Washington DC: Institute for Energy Research, 2009). Available at: http://instituteforenergyresearch.org/wp-content/uploads/2009/05/2.15.13-IER-Web-LevelizedCost-MKM.pdf

20 Ibid. and William Korchinski, *The Limits of Wind Power*, (Los Angeles: Reason Foundation, Policy Study 403, October 2012), available at: http://reason.org/files/thelimitsofwindpower.pdf and Glenn R. Schleede, *The True Cost of Wind is Always Underestimated and its Value is Always Overestimated*, (Washington, D.C.: Science and Public Policy Institute, 2010). Available at: http://michigan.gov/documents/energy/High_Cost_and_Low_Value_of_Electricity_from_Wind1_417752_7.pdf

21 Joost de Gouw, David Parrish, Greg Frost and Michael Trainer, "Reduced Emissions of CO_2, NOx and SO_2 from U.S. Power Plants Due to the Switch from Coal to Natural Gas with Combined Cycle Technology," *Earth's Future*, Vol. 2 (2), pp. 75–82, February 2014. Available at: http://onlinelibrary.wiley.com/doi/10.1002/2013EF000196/full. See also: U.S. Energy Information Administration, U.S. Energy-Related Carbon Dioxide Emissions, 2013, Washington, D.C.: U.S. Department of Energy. Available at: http://www.eia.gov/environment/emissions/carbon/pdf/2013_co2analysis.pdf

22 Richard Tol, "The Social Cost of Carbon: Trends, Outliers and Catastrophes," Economics E-journal, Vol. 2, August 2008. Available at: http://www.economics-ejournal.org/economics/journalarticles/2008-25

[23] Ibid.

[24] http://www.econ.yale.edu/~nordhaus/homepage/

[25] http://climatecolab.org/resources/-/wiki/Main/PAGE

[26] http://www.fund-model.org/

[27] Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," Washington, DC: U.S. Environmental Protection Agency, February 2010, p.16. Available at: http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf

[28] Richard Tol, "The Social Cost of Carbon: Trends, Outliers and Catastrophes," Economics E-journal, Vol. 2, August 2008. Available at: http://www.economics-ejournal.org/economics/journalarticles/2008-25.

[29] Frank Ackerman, Stephen J DeCanio, Richard B. Howarth and Kristen Sheeran, "The need for a fresh approach to climate change economics," in "Workshop Proceedings: Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond," May 2010, pp. 159–181. Available at http://www.c2es.org/docUploads/ackerman-decanio-howarth-sheeran-climate-change-economics.pdf. Hereinafter, Ackerman et al., "Fresh Approach."

[30] M. Madhu and Jerry L. Hatfield, "Elevated carbon dioxide and soil moisture on early growth response of soybean," *Agricultural Sciences* Vol. 6 (2), 2015. http://file.scirp.org/Html/11-3001041_54298.htm

[31] Renu Pandey, Krishna Kant Dubey, Altaf Ahmad, Rakshanda Nilofar, Rachana Verma, Vanita Jain, Gaurav Zinta and Vikas Kumar, "Elevated CO_2 Improves Growth and Phosphorus Utilization Efficiency in Cereal Species under Sub-Optimal Phosphorus Supply," *Journal of Plant Nutrition*, 9 December 2014. http://www.tandfonline.com/doi/abs/10.1080/01904167.2014.983116#.VQsQ-Y7F98E . See also Malin Broburg, "Effects of elevated ozone and carbon dioxide on wheat crop yield – Meta-analysis and exposure-response relationships," University of Gothenbrug Faculty of Science, http://bioenv.gu.se/digitalAssets/1516/1516890_malin-broberg.pdf

[32] Jinyang Wang, Cong Wang, Nannan Chen, Zhengqin Xiong, David Wolfe and Jianwen Zou, "Response of rice production to elevated [CO_2] and its interaction with rising temperature or nitrogen supply: a meta-analysis," *Climatic Change*, 11 March 2015.

[33] Delphine Derying, *Climate Change and Global Crop Yields: Impacts, Uncertainties and Adaptation*, University of East Anglia PhD Thesis, 2014. Available at: http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.630136

[34] In a quadratic function, damage is proportional to the square of the change in temperature, whereas in a cubic function, damage is proportional to the cube of the change in temperature. To see the difference in effect, consider two functions, in the first damage = (temperature change) squared, while in the second damage = (temperature change) cubed. Now, suppose that the temperature rises by one unit in each period, then in the first three periods it will rise by 1, 2 and then 3 units above the previous level. If damage follows the first, quadratic function, then the respective damage will be 1 in period 1, 4 in period 2 and 9 in period 3. Meanwhile, if the damage follows the second, cubic, function, it will be 1 in period 1, 8 in period 2 and 27 in period 3.

35 Ivan Rudik, "Targets, Taxes and Learning: Optimizing Climate Policy Under Knightian Damages," Working Paper, January 19, 2015. Available at: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2516632

36 Weitzman has developed his argument in a series of papers beginning in 2007. See e.g. Martin L. Weitzman, "Fat Tailed Uncertainty in the Economics of Catastrophic Climate Change," *Review of Environmental Economics and Policy*, 2011, pp. 275–292. Available at: http://www.macalester.edu/~wests/econ231/Rev%20Environ%20Econ%20Policy-2011-Weitzman-275-92.pdf

37 Ackerman et al. "Fresh Approach" at p. 169.

38 Ibid.

39 Ibid. at 170.

40 Specifically, welfare, W, is usually assumed to be given by a function of the form W $=\int_0^\infty e^{-\rho t}\,U[C(t)]dt$, where ρ is the rate of (pure) time preference, t is time, U is "utility," and C(t) is consumption at time t. See e.g.: William D. Nordhaus, "A Review of the Stern Review on the Economics of Climate Change," *Journal of Economic Literature*, Vol. XLV, September 2007, pp. 686 –702, at p. 691.

41 Ackerman et al., "Fresh Approach," at p. 165.

42 A further reason for being skeptical about using individual time preference as part of the basis for discounting the future is that at any point in the future an increasing proportion of the individuals present will not have been alive when the analysis was conducted. This may seem trivial but it matters greatly, since the preferences of unborn people cannot be known. Moreover, the individuals who are born in the future owe their existence and hence preferences to the actions taken today. That poses a fundamental problem for any attempt to use utilitarian criteria as the basis for making choices about the future. (See for example Joanna Pasek, "Environmental Policy and The Identity Problem," CSERGE Working Paper 93-113, 1993, http://eprints.ucl.ac.uk/18378/1/18378.pdf.) But it does not justify setting the rate of pure time preference to zero. If anything, it suggests the rate of pure time preference in a cost-benefit analysis should be set at a rate consistent with discounting to zero the preferences of individuals born after any action taken consequent on that analysis. If that seems like a repugnant conclusion, then perhaps the problem is with the utilitarian framework of cost-benefit analysis and not with the concept of pure time preference.

43 Mathematically, this is: $r_t = \rho + \eta g_t$.

44 For a discussion of the Ramsey formula and the debates over use of market interest rates as a proxy, see: Kenneth J. Arrow, Maureen L. Cropper, Christian Gollier, Ben Groom, Geoffrey M Heal, Richard G. Newell, William D. Nordhaus, Robert S. Pindyck, William A. Pizer, Paul R. Portney, Thomas Sterner, Richard S. J. Tol and Martin Weitzman, "How Should Benefits and Costs Be Discounted in an Intergenerational Context? The Views of an Expert Panel," Resources for the Future Discussion Paper, RFF DP 12-53, December 2012. Available at: http://www.rff.org/RFF/Documents/RFF-DP-12-53.pdf

45 Ibid., at p. 171.

46 Ackerman et al., "Fresh Approach," p. 172.

47 For a list, see e.g. http://humanknowledge.net/SocialScience/Futurology/Catastrophes.html

[48] Pindyck, “Climate Change Policy,” at p. 869.

[49] Peter Howard, *Omitted Damages: What’s Missing from the Social Cost of Carbon*, Environmental Defense Fund, Institute for Policy Integrity, and Natural Resources Defense Council, March 2014. Available at: http://costofcarbon.org/files/Omitted_Damages_Whats_Missing_From_the_Social_Cost_of_Carbon.pdf

[50] Dudley is now director of the GWU Regulatory Studies Center and Mannix is a visiting scholar at the Mercatus Center.

[51] Susan E. Dudley and Brian Mannix, “The Social Cost of Carbon,” *Engage*, Volume 15(1), July 24, 2014. http://www.fed-soc.org/publications/detail/the-social-cost-of-carbon

[52] Circular A-94, “Guidelines and discount rates for benefit-cost analysis of federal programs,” Washington, DC: Office of Management and Budget, at p. 9.Available at: https://www.whitehouse.gov/sites/default/files/omb/assets/a94/a094.pdf

[53] William D. Nordhaus, “A Review of the Stern Review on the Economics of Climate Change,” *Journal of Economic Literature*, Vol. XLV, September 2007, pp. 686–702, at p. 690. Available at: http://www.econ.yale.edu/~nordhaus/homepage/documents/Nordhaus_stern_jel.pdf

[54] Richard Tol, “The Social Cost of Carbon,” *Annual Review of Resource Economics*, *Annual Reviews*, Vol. 31 (1) pp. 419-433, hereinafter, “Richard Tol, Social Cost, 2011.” Available at: https://ideas.repec.org/a/anr/reseco/v3y2011p419-443.html

[55] Ibid. Quotation from pre-publication working paper version, available at https://ideas.repec.org/p/esr/wpaper/wp377.html, at p. 18.

[56] Tomas Havranek, Zuzana Irsova, Karel Janda and David Zilberman, “Selective Reporting and the Social Cost of Carbon,” published online, February 19, 2015, Available at: http://meta-analysis.cz/scc/

[57] Ibid.

[58] Stephanie Waldhoff, David Anthoff, Steven Rose and Richard S. J. Tol, “The marginal damage costs of different greenhouse gases: an application of FUND,” *Economics – The Open Access, Open-Assessment e-journal*, Vol. 8 (2014-31), pp. 1-33, 2014.

[59] For example, Circular A-94 states: “International Effects. Analyses should focus on benefits and costs accruing to the citizens of the United States in determining net present value. Where programs or projects have effects outside the United States, these effects should be reported separately.” Circular A-94, “Guidelines and discount rates for benefit-cost analysis of federal programs,” Washington, DC: Office of Management and Budget, p. 7.

[60] $1.01^{70}=2.0067$

[61] Interagency Working Group, “Technical Support Document,” p. 13.

[62] In its Technical Support Document (ibid. at p. 14), the IWG reproduces various estimates of the probability density function for the equilibrium climate sensitivity that were included in the IPCC’s Fourth Assessment Report. See: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch9s9-6-2.html

63 Detlef P. van Vuuren, Jason Lowe, Elke Stehfest, Laila Gohar, Andries F. Hof, Chris Hope, Rachel Warren, Malte Meinshausen and Gian-Kasper Plattner, "How well do integrated assessment models simulate climate change?" *Climatic Change*, published online 11 December 2009, Available at: http://se-server.ethz.ch/staff/af/fi159/V/Va139.pdf

64 Ibid. at page 14, Figure 4.

65 John C. Fyfe, Nathan P. Gillett and Francis W. Zwiers, "Overestimated global warming over the past 20 years," *Nature Climate Change*, Vol. 3, September 2013, pp. 767–769.

66 John R. Christy, "Public Comment on EPA proposed rule for existing carbon-burning power plants EPA-HQ-OAR-2013-0602-0001," available at: http://www.globalwarming.org/wp-content/uploads/2014/12/ChristyJR_EPA_2014_PublicComment.pdf

67 Kyle J. Swanson, "Emerging selection bias in large-scale climate change simulations," *Geophysical Research Letters*, Vol. 40 (12), pp. 3184–3188, 28 June 2013. Available at: http://onlinelibrary.wiley.com/doi/10.1002/grl.50562/abstract

68 Patrick Michaels and Chip Knappenberger provide a useful non-technical summary of these estimates on the Cato Institute's website: http://www.cato.org/blog/collection-evidence-low-climate-sensitivity-continues-grow

69 Ibid.

70 IPCC, "Summary for Policymakers," in T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, (New York: Cambridge University Press, 2013), p. 16. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf

71 Nicholas Lewis and Judith Curry, "The implications for climate sensitivity of AR5 forcing and heat uptake estimates," *Climate Dynamics*, September 2014 (http://link.springer.com/article/10.1007/s00382-014-2342-y); a pre-print version is here: https://niclewis.files.wordpress.com/2014/09/lewiscurry_ar5-energy-budget-climate-sensitivity_clim-dyn2014_accepted-reformatted-edited.pdf.

72 Nicholas Lewis, "The implications for climate sensitivity of Bjorn Stevens' new aerosol forcing paper," http://climateaudit.org/2015/03/19/the-implications-for-climate-sensitivity-of-bjorn-stevens-new-aerosol-forcing-paper/

73 "Technical Support Document," February 2010, at p. 10.

74 Jennifer F. Bobb, Roger D. Peng, Michelle L. Bell and Francesca Dominici, "Heat-Related Mortality and Adaptation to Heat in the United States," *Environmental Health Perspectives*, Vol. 122(8), pp. 811–816, 2014. Available at: http://ehp.niehs.nih.gov/wp-content/uploads/122/8/ehp.1307392.pdf

75 Richard Tol and H. Dowlatabadi, "Vector borne diseases, development & climate change," *Integrated Assessment,* Vol. 2, pp. 173–181, 2001.

76 Natasha Gilbert, "Cross-bred crops get fit faster: Genetic engineering lags behind conventional breeding in efforts to create drought-resistant maize," *Nature,* Vol. 513, p. 292, 18 September 2014. Available at: http://www.nature.com/news/cross-bred-crops-get-fit-faster-1.15940.

Reason

5737 Mesmer Ave.
Los Angeles, CA 90230
310-391-2245
reason.org