

THE SOCIAL COST OF CARBON: AN UNFOLDING VALUE

Robert Mendelsohn

School of Forestry and Environmental Studies, Yale University, New Haven, CT USA

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I. Introduction

The social cost of carbon is the present value of damages caused by a ton of emissions in a particular time period. Carbon emissions contribute to the concentration of greenhouse gases around the world. An emission of carbon (and other greenhouse gases) increases worldwide atmospheric concentrations, which contributes to increased solar radiation and thus higher temperatures globally. Higher temperatures in turn change climatic conditions throughout the world, causing benefits in cool places and damages in warm places. The consequences of greenhouse gas emissions are therefore not local but rather global and reflect both benefits and damages caused across the planet. Because each ton is expected to remain in the atmosphere for a long period, each emission contributes to a stream of damages in many future periods. The social cost of carbon counts this entire stream. However, it is important to capture the timing of these effects because there are long delays between emissions and changes in temperature and eventual damages. Taking the present value of the stream adjusts for these long delays by discounting the damages back to the present. By discounting the damages back to the moment that mitigation is considered, the social cost of carbon can be balanced against the marginal cost of mitigation (the cost of preventing the emission from occurring). Because the damages from greenhouse gases are global, the estimation of the social cost of carbon must also be global. Given that the consequences are unequally distributed across many nations, the valuation of damages is a contentious affair. Adding the inherent uncertainty of predicting damages far into the future, there is widespread agreement that measuring the social cost of carbon is difficult. Nonetheless, it is an essential component in determining global carbon policy and an important guide to prudent local policy.

An additional ton of emission causes consequences that change as more and more greenhouse gases accumulate in the atmosphere. The harmful effects gradually increase with more carbon and the beneficial effects diminish. The social cost of carbon consequently is a dynamic concept. It leads to different values over time. The value is expected to rise over time as the greenhouse problem unfolds.

Because carbon emissions throughout the globe cause the same damage to the planet, there is only one value of social cost of carbon at each moment. Regardless whether an emission is made in a remote island state or in Great Britain, there is a single value of the damages. Individual countries cannot choose their own social cost value, although they are free to determine their national carbon policy. The social cost of carbon must be calculated for the globe as a whole. Not only must the measurement of social cost be anchored in the best available science, it must also be anchored in the best available measurements of the value of the consequences across nations.

In the following paper, we recount the history of the social cost of carbon. Because the social cost of carbon follows cause and effect from emissions through final consequences, it encompasses research on economic growth, energy, carbon and other greenhouse emissions, atmospheric chemistry, solar radiation, carbon cycles, climate modelling, ocean modelling, ecosystem modelling, impacts research, and valuation. It is not possible to cover such a broad scope in detail and so we heavily rely on the Intergovernmental Panel on Climate Change reports for overviews of the relevant science.

This paper begins with a brief review of the theory behind controlling greenhouse gases. The theory highlights the central role of the social cost of carbon. The theory also illustrates the role

of the discount rate and the dynamic nature of the social cost of carbon. We then turn to an integrated assessment model that illustrates the many logical steps required to follow cause and effect and how each science contributes to our understanding. We reserve the largest section of the paper to review the empirical evidence concerning final impacts. We demonstrate how these values have changed over time and why. The paper concludes with some policy observations for the globe and for Great Britain in particular.

II. Abstract Theory

The most basic principle in managing environmental pollution is that society wants to minimize the sum of the environmental damages and mitigation costs. With a long-lived problem such as greenhouse gases, this requires society to take a long run view. Society must minimize the present value of the mitigation costs and the present value of the damages. The seminal paper to capture this basic principle in the greenhouse context was done by Nordhaus (1991). In this section, we rely on Falk and Mendelsohn (1993) largely because of its simplicity.

The most basic principle is to choose a path of carbon control that minimizes the sum of the abatement costs $C(Q(t))$ and environmental damages $D(S(t))$:

$$\text{Min } \int C(Q(t)) \exp(-\gamma t) dt + \int D(S(t)) \exp(-\gamma t) dt , \quad [1]$$

where $S(t) = S(t-1) + Q(t) - \lambda S(t)$,

and $Q(t)$ is global emissions, t is time, r is the market interest rate, γ is the social discount rate, $S(t)$ is the stock of carbon (greenhouse gases) in the atmosphere, and λ is the decay rate of the stock. The first line in equation [1] reflects the costs to society discounted back to the present. The second line describes how the stock changes over time. It clearly increases with emissions but it also has a decay effect that tends to push the stock back towards its natural equilibrium. As long as emissions are greater than the decay, the stock increases over time.

In order to solve this problem, one needs to differentiate equation [1] with respect to emissions and compute the first order conditions:

$$MC(Q(t)) = MD(S(t)) / (\gamma + \lambda) \quad [2]$$

Equation [2] states that the marginal cost of abatement in each year should be equated with the present value of the damages that a marginal ton causes each year. The appropriate discount rate is the sum of the social discount rate and the decay rate. In the case of carbon, the decay rate is quite small (.005) (implying a life expectancy of atmospheric carbon of 200 years). There is a substantial debate in the literature concerning what value to use for the social discount rate (Arrow et al 1996). The important point is that one cannot choose a separate discount rate for greenhouse gases from all other problems. The discount rate is the price of time, not the value of greenhouse gases. Whatever rate is chosen must be consistent with other public investments and tax policy. If the mitigation costs compete with private investment for savings, the opportunity cost of the funds is the market interest rate, what they would otherwise have earned society (see Arrow et al 1996).

The left hand term in equation [2] is the marginal cost of mitigation, the cost of preventing emissions. The model implies that the marginal cost of carbon should be equated across the

planet. Given any specific carbon target, equilibrating the marginal cost of carbon across all opportunities will achieve that target at the least cost to society. If any one country spends far more on controlling carbon than the rest of the globe, it will be effectively wasting resources that could have been far more effectively used elsewhere. That includes, of course, spending the mitigation resources controlling carbon in other countries.

The right hand side of equation [2] is the social cost of carbon. It is the present value of all the future net damages from a ton of emission in period t . The social cost of carbon is very important because it dictates how much everyone should spend on carbon mitigation each period. Ideally, one should not control a ton of carbon whose mitigation costs more than the social cost of carbon that period.

Equation [2] highlights another important principle. The social cost of carbon is tied to the stock of carbon in the atmosphere at the moment of emission. It reflects the additional consequences of making the stock slightly larger. It is not tied to the consequences of future emissions. Future emissions are evaluated when they are emitted. The social cost of carbon is consequently dynamic. As the stock of carbon in the atmosphere increases, the marginal damage is expected to rise. Over time, the social cost of carbon should increase. That in turn implies a dynamic control strategy that begins with only low cost mitigation alternatives but gradually includes more and more expensive control options over time.

It is a common mistake that some global warming observers confuse the consequences of current emissions with the damages caused by future emissions. Future emissions will likely have a high social cost of carbon if global warming unfolds in a harmful direction. That does not imply that current emissions also have a high social cost of carbon. Current emissions should be evaluated on the basis of what they cause to happen. The stream of marginal damages caused by current emissions is the same whether future emissions increase dramatically or disappear completely. The social cost of carbon for emissions today should not include the damages caused by future emissions. These additional damages should be assessed against the future emissions alone.

III. Integrated Assessment

It is one thing to write a general formula for controlling a cumulative pollutant, it is quite another to organize all the science required to implement the concept. Integrated assessment organizes the myriad sciences that contribute to understanding the link between cause and effect with greenhouse gases. As mentioned above, the first model to put together this vast array of information was Nordhaus [1991]. Subsequently, there have been a host of economic integrated assessment models for greenhouse gases that capture ever more detail and new science (for example: Nordhaus 1994; Nordhaus and Boyer 2000; Peck and Teisberg 1993; Manne et al 1995, Tol 1996; 1999).

Figure 1 displays a simple schematic that links the major components of an integrated assessment model for greenhouse gases. The model moves through causal mechanisms from emission control through final damages. The schematic highlights six key steps: emissions, ambient concentrations, climate and ocean changes, ecosystem changes, social impacts, and valuation. Each of these steps requires the service of at least one discipline and often more than one.

All of the steps listed in Figure 1 must be carried forward through time. As the theory dictates, the problem requires long term modelling. It is not correct to match current costs with current damages. Current costs must be linked with a long stream of future damages. The model consequently must be solved far into the future. Every step of the model is consequently burdened with predicting events across at least several decades and possibly the next century. As events occur further and further into the future, they become more uncertain. However, it is not possible to determine even near term policies without having some idea what the consequences of current emissions are for many decades into the future. Partly because of the long lags between emissions and climate changes (30 years) and partly because of the long schedule of damages once climate changes (200 years), it is critical to forecast what current emissions do to future impacts. Although we clearly will learn about global warming through future changes, it is very likely that global warming policy will always be shrouded in uncertainty about the distant future.

The first step of the integrated assessment model in Figure 1 determines the level of emissions in each period and mitigation costs. Forecasting future emissions and mitigation costs has been the focus of many economic and engineering studies (see Metz et al 2001). Forecasting emissions is not straightforward because it depends upon future economic growth and energy use. The difficulty of forecasting far into the future has led to a wide range of cost estimates (see Metz et al 2001). The actual cost, of course, depends upon how aggressively policy tries to reduce emissions. One general conclusion of the literature is that it will be expensive to engage in extensive mitigation that will keep concentrations from rising far above current levels (Metz et al 2001). The question about how deeply to control carbon emissions is not an academic exercise but rather a very central concern in greenhouse gas policy and an important social investment decision.

The second step in the model determines how concentrations change with emissions and changes in natural sinks and sources. Studying this problem has been the focus of both atmospheric scientists who have made many detailed measurements of greenhouse gases (see Houghton et al 1996; 2001) as well as ecologists who have built ever more detailed carbon cycle models (see Prentice et al., 2001). The models and measurements reveal that greenhouse gases are building up in the atmosphere, though not quite as fast as society is adding emissions. The measurements suggest that sinks in the carbon system are absorbing some of the additional emissions. One of the large uncertainties in the integrated assessment model concerns how these sinks might behave in the future and whether some sinks could become sources as the planet warms.

The third step of the model captures how the oceans and climate change together. This has been the singular focus of a large number of oceanographers and climate scientists (Houghton et al 1996, 2001). They have very carefully measured historical records as well as projected what might happen into the future. There is growing evidence that greenhouse gas emissions have already warmed the planet 0.5C (Houghton et al 2001). However, of much greater concern, is what will happen if emissions continue unabated. The most recent projections suggest that a zero mitigation policy would warm the planet by from 1.4C to 5.8C by 2100 (Houghton et al 2001). This is a very wide range of possible climate outcomes from a very mild case to a relatively severe story. Unfortunately, the 2001 IPCC report made no attempt to identify how likely each outcome might be. This has handicapped careful estimation of the social cost of carbon because it is not clear whether the high end of the temperature range is likely or a low probability event. It is further not clear what the expected value of the temperature change is

supposed to be. Hopefully, the next IPCC report will address this serious shortcoming in the presentation of the science.

The fourth step of the model captures changes in ecosystems including changes in forests and crops. Ecologists predict that biomes will gradually move poleward as a result of warming and changes in precipitation patterns (see Watson et al 1995). The speed of this change, however, is not clear and the interim states-of-nature as systems move from type to type is also not clear. One scenario implies widespread devastation from fires and insect outbreaks that disrupt the southern (northern) edge of each biome in the northern (southern) hemisphere. Biomes to the south will gradually move into this disrupted space but the transition could take many decades or even centuries. What ecological services would be provided in the interim is not clear. Another scenario is that species gradually move north by outcompeting more northern species in regeneration. This scenario does not forecast widespread disruption but rather a gradual creeping process. How quickly the process would take and what happens during interim mixing remains a question mark for this scenario as well. Along with moving biomes, the modellers also predict changes in bioproductivity (Watson et al 1995). The changes in bioproductivity and the changes in the biomes must be modelled together as they are simultaneous and interactive. Agronomists have also measured changes in crop productivity that might occur with warming.

Another important topic covered in this step is the impact of carbon fertilization. Through both laboratory and open field experiments, it has been determined that carbon dioxide acts as a fertilizer to almost all plant species. The carbon fertilization effect appears to be logarithmic which implies that it will be positive but diminishing over time. On average, crop yields are expected to increase 30% with a doubling of carbon dioxide (Reilly et al., 1996). The magnitude of this effect for crops may be much less for trees in natural conditions as they may be limited by the availability of other nutrients. However, with crops, farmers already add fertilizer so that the nutrient constraint is not generally binding.

The fifth step measures the social impact of all the changes in both market and nonmarket sectors. The market impacts include changes in agriculture, timber, water, energy, and coastal resources (see Watson et al 1995; McCarthy et al 2001). The nonmarket effects include the changes in biomes and bioproductivity which lead to changes in wildlife habitat, the human health effects from air pollution, water pollution, heat stress, and vector borne diseases, and the amenity values of weather (see Watson et al 1995; McCarthy et al 2001).

Impacts could be measured in physical terms such as loss of bushels of corn, or potential new cases of diseases, but ultimately they need to be converted to the same units of value as mitigation costs (Pearce et al 2001). The final step in the model captures what values local people assign to the changes that they experience. These values need not be the same across the planet. The key is that the analysis uses the values of the people who actually experience the effects. Valuation is clearly a contentious but critical step in the integrated assessment model.

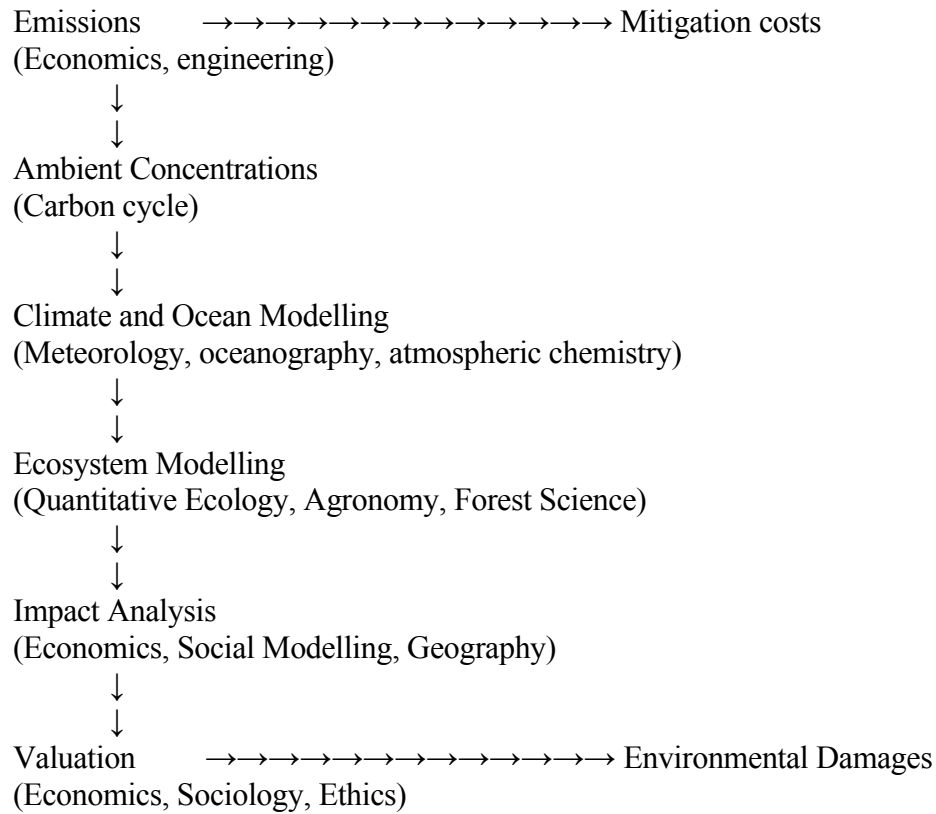
Some scientists, model builders, may have the impression that they can substitute their own values in this last stage (see criticism by Schneider 1997). However, it is not the values of the scientists that are required but rather the values of the victims. Valuation must rely on proven methods to elicit values from the directly affected individuals. In the case of market impacts, economics has already developed many powerful valuation methods. However, the nonmarket impacts are much more difficult to value. The valuation of nonmarket impacts is one of the most poorly developed sections of the integrated assessment model.

Nonmarket impacts are changes in goods and services that are not traded in markets. These goods and services are often public goods, shared by many individuals at a time. For example, wildlands can be enjoyed by many people simultaneously to hunt, hike, camp, or just view. In many circumstances, people are not required to pay to enjoy these services because the land or at least access to the land may be owned by the government. The absence of a fee, however, does not imply the service has no value. There simply is not a market for it. The valuation of nonmarket services requires more than simply observing prices because in the absence of markets, there are no prices. Some other valuation method must be employed. Valuation efforts have increased dramatically in the last two decades to capture many nonmarket services including recreation sites and human health. However, few studies have addressed nonmarket services peculiar to global warming, such as shifting ecosystems.

One of the biggest problems in the valuation of global warming, however, has been the inclusion of adaptation. Victims will tend to react to negative stimulus by avoiding damages when possible. For example, farmers will stop growing crops that regularly fail. The early climate change literature did very little to include adaptation. They consequently predicted that there would be very large damages that extended far into the future from climate change. These early studies are reviewed in the comprehensive review of early literature by Pearce et al (1996). Subsequent research, however, has revealed that adaptation could be substantial for an environmental change that occurs gradually over many decades (Mendelsohn and Neumann 1999; Mendelsohn 2001). Even hard to change resources such as forests can gradually be molded over a time frame this long. Adaptation changes the results. Temperature still has a hill shaped relationship with respect to many sectors but the response hills become far flatter with adaptation. With adaptation, impacts are far less severe. Adaptation is a critical component of valuation. Unfortunately, few of the nonmarket studies have yet to include adaptation. For example, the health studies have yet to include a public health response and the ecological studies have yet to include any management responses.

The completion of the integrated assessment model provides a link between emissions and damages. In the next section of the paper, we discuss the results in the literature. Not only are the values expected to change as greenhouse gases accumulate, but it is also apparent that the values have changed as research has revealed new insights.

Figure 1: Integrated Assessment Schematic



IV. Estimates of the social cost of carbon

What we are interested in measuring is the present value of damages caused by a ton of emissions over time. Before turning to these values, however, it is helpful to examine what the impact literature actually measured. The first estimates of the impact of climate change were heavily influenced by available climate forecasts. In order to compare climate model outputs, climate scientists focused on the climate change that would result from doubling greenhouse gases. Early impact studies consequently focused on the impacts that would occur if greenhouse gases doubled. As a convention, they explored the implications of this new climate on a 1990 economy. This convention, of course, is problematic because the climate change associated with doubling will not occur in 1990 but rather in approximately 2060. Early authors, however, took this convention seriously and so did not consider how things would change with time or with a gradually changing climate system.

There are several miscellaneous studies of selected sectors in relatively local settings through the 1980's. These studies are hard to calibrate because they used very different climate change assumptions and evaluated isolated impacts. However, in 1989, the United States Environmental Protection Agency put together the first comprehensive analysis of all vulnerable sectors in the United States (Smith and Tirpak 1989). Although this comprehensive evaluation did not quantify the welfare impacts of climate change, the study provided sufficient background information for analysts to subsequently make the first valuations of aggregate impacts.

The first aggregate estimates were generated by Nordhaus (1991) but many authors quickly followed suit. These initial aggregate estimates are captured in the following table from Pearce (1996). Table 1 presents what five different authors believed would happen to the 1990 United States economy if greenhouse gases doubled. All but Titus estimated that the annual damages would be about \$55 to \$74 billion or between 1 and 1.5% of 1990 GDP. There are reasons to dismiss Titus as an outlier. His estimate for timber effects is implausible given the small size of this sector. The estimates for air and water pollution are based on abatement costs required to keep ambient concentrations fixed, not expected damages. Although clearly the sign is correct on these estimates, the magnitudes are likely exaggerated. Reducing these three estimates to reasonable levels would bring the Titus aggregate estimates in line with the other authors. It is interesting to note, however, that despite the general agreement of all the authors concerning aggregate effects, they have wildly different estimates of the effects in each sector.

The aggregate estimates of the US studies led to a consensus at this time that developed countries would suffer damages of 1-1.5% of GDP. Much less was known about developing countries. Fankhauser (1995) estimated that developing countries would suffer damages of about 1.6%. Tol (1995) was much more pessimistic estimating damages for developing countries averaging 2.7%. Both authors expected developing countries to have larger damages than OECD countries because a greater fraction of their economy was vulnerable (in agriculture) and because many lives were at risk in developing countries from vector borne diseases and hurricanes.

Based on these estimates of global damage, various integrated assessment models have computed what the social cost of carbon should be. The estimates are reported in Pearce (1996). They range from \$7 to \$20 per ton for the next decade and rise to \$10 to \$30 per ton by 2030. These values reflect what the early impact literature predicted would occur across the planet.

Table 1: Initial Estimates of Aggregate Climate Damages for the United States (billions of 1990 USD/year)

Sector	Cline	Fankhauser	Nordhaus	Titus	Tol
Agriculture	17.5	8.4	1.1	1.2	10.0
Timber	3.3	0.7	...	43.6	...
Energy ^a	9.9	7.9	1.1	8.1	...
Sea Level Rise	7.0	9.0	12.1	5.7	8.5
Water supply	7.0	15.6	...	11.4	...
Total Market	44.7	41.6	14.3	70.0	18.5
Mortality	5.8	11.4	...	9.4	37.4
Migration	0.5	0.6	...	...	1.0
Hurricanes	0.8	0.2	...	...	0.3
Leisure/amenity	1.7	...	...	...	12.0
Water pollution	...	...	...	32.6	...
Urban Infrastructure	0.1	...	...	...	...
Air Pollution	3.5	7.3	...	27.2	...
Species Loss	4.0	8.4	...	...	5.0
Total Non-market	16.4	27.9	41.2	69.2	55.7
Total	61.1	69.5	55.5	139.2	74.2

^aEnergy costs include electricity, other heating and mobile air conditioning.
Source: Pearce et al 1996.

Since these early studies were completed, there has been a wave of new empirical impact studies that have captured new scientific insight and endogenous adaptation (see Mendelsohn and Neumann 1999 and Mendelsohn 2001). The new studies no longer value impacts in 1990 but rather seek to project what the impacts will be in the future as climate changes. Because the future economy is expected to be larger, the absolute magnitude of the damages is expected to increase. However, because many of the vulnerable sectors of the economy such as agriculture and timber are expected to shrink relative to GDP, the impacts in proportion to GDP are expected to shrink.

In the process of recognizing that climate change will unfold slowly, the new impact studies have sought to more fully capture adaptation. Farmers are expected to shift crops as climate changes, sea walls are expected to be built as needed to control sea level rise, foresters are expected to gradually adjust their stocks of trees, and water is expected to be reallocated to its highest use given changing conditions. Many of these adaptations are simply in the best interest of firms and people living through these changes. There is every reason to expect that they will be undertaken. However, some adaptations require the coordination of many users such as the building of sea walls or the reallocation of water. These adaptations will require government involvement and it is not certain that governments will respond efficiently to these new demands. Some of this new literature, which assumes efficient government response, may consequently be optimistic (Mendelsohn 2000).

A very important insight of this new literature is that sectors tend to have hill-shaped relationships with temperature. That is, each sector has an optimal temperature. Any change to either the cooling side or the warming side of this optimum causes a reduction in value. This hill-shaped response function implies that the impacts of warming will not be the same across the planet. Places that are currently cool will climb the hill with warming whereas places that are too warm will fall down the hill. One of the insights of this new research is that there will be both benefits and damages from global warming in contrast to the estimates in Table 1. Mid to high latitude countries are likely to see benefits from modest warming of 1-2.5C whereas tropical countries may well be harmed even from these mild climate changes. Polar countries may continue to benefit even with more severe temperature changes but temperate countries will begin to pass their optimum temperatures and see damages. The damages in the tropical regions are expected to get ever more severe as temperature climbs.

Another important change in this literature is that the ecosystem science has become more optimistic. Whereas early ecosystem studies focused on bad things that could happen with climate change, a new wave of ecosystem studies report all the changes that might happen (see for example Haxeltine and Prentice 1996). These new studies indicate that a world that is warmer, wetter, and CO₂ enriched may well be beneficial to plants in general. Forests may expand (although at the likely expense of tundra) and become more productive and crops are likely to become more productive globally as well. When incorporated into the impact model, these new forecasts imply global warming will lead to global net benefits for agriculture and forestry (Reilly 1996; Sohngen et al. 2002). Of course, these benefits will not be universal. Places that are currently warm (tropics) may not do as well and may even be harmed by warming.

Table 2 provides new estimates of what might happen to the United States given these new research findings. The table presents four scenarios: a mild and severe temperature change coupled with no increases and a 15% increase in precipitation. It is quite clear that the climate

Table 2: New Estimates of Climate Impacts on the United States Economy in 2060 (billions of 1998 USD/year)

Sector	Climate Scenario			
	No Precipitation Change		15% Precipitation Increase	
	2.5C	5.0C	2.5C	5.0C
Agriculture	25.5 (17 to 33)	14.1 (-7 to 24)	26.1 (16 to 36)	17.0 (-7 to 27)
Timber	1.5 (1 to 2)	1.5 (1 to 2)	6.9 (6 to 8)	7.8 (6 to 10)
Energy	-5.3 (-10 to -1)	-21.3 (-32 to -15)	-8.3 (-14 to -3)	-26.9 (-37 to -17)
Coastal ¹	-0.2 (-0.4 to -0.1)	-0.4 (-1 to -0.2)	-0.2 (-0.4 to -0.1)	-0.4 (-1 to -0.2)
Water	-4.8 (-9 to -2)	-11.3 (-5 to -25)	0.6 (-5 to +5)	-5.4 (-15 to 5)
Total	16.7 (3 to 29)	-19.9 (-49 to -2)	25.1 (10 to 38)	-7.8 (-41 to 11)
% 2060 GDP	0.08%	-0.09%	0.12%	-0.04%

Source: Mendelsohn and Smith (2001).

¹The sea level rise estimates assume that higher temperatures lead to more sea level rise.

scenario matters. The two scenarios examining a 2.5C warming suggest net economic benefits to the United States. The possibility that mild warming could be beneficial to any country was not recognized in the early literature. Of course with more warming, effects in mid-latitude countries do become harmful. There are net damages associated with a 5C warming. Because the benefits in the agriculture sector are offsetting the damages in energy, water, and coasts, the overall net results are surprisingly small. The effects in Table 2 as a percent of GDP are an order of magnitude smaller than in Table 1.

Because the effect of temperature change depends upon current temperature, the impacts within at least a large country will also not be uniform. In a regional analysis of the United States, all regions benefited if the climate change was 1.5C because in this case carbon fertilization dominates and helps every region (Mendelsohn 2001). As warming increased to 2.5C, benefits in the northern regions increased but then they began to shrink with 5C warming. In the south, warming to 2.5C eliminated the benefits from carbon fertilization and with warming of 5C, large damages began to appear.

These regional results hint that effects for high latitude countries are likely to be even more beneficial than they are for the United States. Warming is more beneficial the cooler your initial conditions and climate models predict more warming in the high latitudes than in the rest of the world. A much more pessimistic vision extends to the low latitudes. As already noted, the low latitude countries depend more on agriculture. The low latitude countries are also already hot and so any further warming is expected to damage agriculture. The low latitude countries also have much more labor-intensive agriculture. In a comparative analysis of India and the United States, the Indian farms were found to be much more climate sensitive than the American farms (Mendelsohn et al 2001). There is every reason to believe that low latitude countries will be more vulnerable to warming than the United States.

In a comparative analysis using many AOGCM's, Mendelsohn and Williams (2003) have forecasted the impacts to each sector of each country around the world. The estimates rely on the American studies for mid to high latitudes (Mendelsohn and Neumann, 1999; Mendelsohn 2001) and the Indian study for low latitude countries (Mendelsohn et al 2001). Separate impacts are estimated for each country based on the climate change predicted in the country, the climate response function, and numerous background factors such as cropland, coasts, GDP, and population. The results in Table 3 report the outcomes in 2100 for two climate models: CSIRO (Gordon and Farrell 1997) and CGCM1 (Boer et al 2000). The two climate forecasts do not include sulfates and so they reflect relatively high predictions of warming of 4.6C and 7.1C. Note that the effects in each region are not the same. The low latitude countries are damaged by warming. With CSIRO, the mid to high latitude countries tend to benefit. With CGCM1, the damages to the low latitude countries increase, the mid-latitude countries begin to be damaged, and the high latitude countries continue to receive benefits. The most striking result in Table 2, however, is that the net global impact is surprisingly small. As the benefits in mid to high latitude countries offset the damages in low latitude countries, the net effect for the globe is between -0.08% to 0.24%. This is an order of magnitude smaller than the early estimates of Tol (1995) and Fankhauser (1995).

Note that there is no row in Table 3 for extreme events. The estimates of changes in climate normals already include the existing level of climate variance. The impact models assume that historic climate variance will continue. At least for the moment, climate scientists are not convinced that

Table 3 Aggregate Climate Impacts in 2100 by Region (billion 1998 USD/year)

Region	CSIRO Climate Model (4.6C)						Total	%GDP
	Agr	Forest	Energy	Water	Coast			
L America	-35.1	0.3	-9.5	-4.5	-0.0	-49.0	-0.23	
Africa	-66.7	0.2	-3.0	-1.4	-0.0	-71.0	-1.56	
Asia	-180.	1.3	-29.1	-15.9	-0.2	-224.0	-0.32	
Oceania	-10.1	0.0	-1.4	-0.5	-0.0	-11.0	-0.48	
N America	34.5	1.2	-28.2	-11.5	-0.1	-4.1	-0.01	
W Europe	29.9	1.1	-4.5	-6.3	-0.1	20.1	0.04	
USSR&EE	179.7	1.0	1.6	-2.0	-0.0	180.2	1.42	
Globe	-47.9	5.1	-74.3	-42.1	-0.5	-159.6	-0.08	
Region	CGCM1 Climate Model (7.1C)						Total	%GDP
	Agr	Forest	Energy	Water	Coast			
L America	-92.7	0.3	-17.8	-8.6	-0.2	-118.9	-0.55	
Africa	-99.1	0.2	-6.0	-2.1	-0.0	-107.0	-2.35	
Asia	-295.5	1.8	-48.4	-21.9	-1.7	-365.7	-0.53	
Oceania	-19.1	0.0	-2.4	-0.8	-0.0	-23.4	-0.89	
N America	9.0	1.5	-44.2	-16.4	-0.7	-50.8	-0.10	
W Europe	8.0	0.8	-8.8	-9.9	-1.1	-11.0	-0.02	
USSR&EE	183.4	1.1	-0.3	-2.9	-0.1	181.3	1.42	
Globe	-305.9	5.7	-127.9	-62.7	-3.8	-494.6	-0.24	

climate variance or extreme events will change because of greenhouse gases. Some models or theories suggest that climate variance and extremes will increase whereas other models suggest that variance and extreme events will decline. Until the climate scientists have evidence to suggest which way it will go, it is premature to include a row for this effect. Similarly catastrophic events are not included in the analysis as well for the same reason. If scientists can assign a probability of a catastrophic event and measure the severity, a high consequence low probability event could readily be included in the analysis. However, until there is plausible evidence supporting such events, it is difficult to give them much weight.

Table 3 also does not include nonmarket effects. Given the high values placed on nonmarket effects in the early literature (see Table 1), completely omitting them is unacceptable. Although quantitative estimates of many nonmarket effects remain as elusive today as when the Second Assessment Report was being prepared, some of the general new findings for market effects probably carry over to nonmarket effects as well. The early impact literature focused on harmful consequences. The literature overlooked possible beneficial effects. The beneficial effects of warming on leisure for example were ignored. Early writers such as Cline (1992) focused on skiing, which would clearly be damaged by warming. Most outdoor recreational activities, however, occur in warm weather and the length of the warm season would increase. New studies of outdoor recreation consequently predict that warming will be beneficial to this sector (Pendleton and Mendelsohn 1998; Loomis and Crespi 1999; Mendelsohn and Markowski 1999). Another important benefit that was overlooked is the amenity value of having a warm climate. In several hedonic wage studies in both Europe and the United States, people expressed a preference for warmer climates (Maddison 2001). At least with moderate warming, there will be large benefits accruing to people living in mid and high latitude countries. Of course, these benefits might not extend to the low latitudes that already have warm climates. In the low latitudes, one may well find that warming leads to amenity damages.

The nonmarket studies are also notorious for leaving out adaptation. Although it may be expensive to manipulate the natural ecosystems of the entire world to facilitate new equilibrium ecosystem outcomes, it is reasonable to imagine that special programs could be developed to focus on endangered species. There is every reason to believe that a concerted effort could substantially limit the number of valuable endangered species lost to warming. Health studies have also conspicuously omitted adaptations. Despite the fact that these studies have been conducted in Schools of Public Health, there is absolutely no public health response built into the model estimates. Instead, the research focuses on potential cases of disease and mortality. Including potential cases as actual mortality suggests that health is an important component in damages (Tol and Downing 2000). However, it is likely that control programs can limit potential cases. American cities in warm climates have avoided losing elderly to heat stress. Developed countries have controlled vector borne diseases such as malaria from actually causing any deaths. These public health responses would severely reduce the mortality figures implicit in the Fankhauser (1995), Tol (1995), and Tol and Downing (2000) estimates. There are many reasons to believe that the original estimates of nonmarket impacts are overestimated by a factor of 10, just like the market impacts.

If the global damages from greenhouse gases are an order of magnitude smaller than previously considered, this implies that the social cost of carbon is also an order of magnitude smaller. Instead of the current social cost of carbon lying between \$7 to \$20 per ton, the new literature implies that the current social cost of carbon probably lies closer to \$1 to \$2 per ton. Similar estimates emerge with Fund 2.0 when a 3% social rate of time preference is included (Tol and

Downing 2000). Of course, this figure would rise over time as carbon accumulates but it may well remain below \$5 per ton for the next 30 years.

Table 3 has a small variation in values to reflect the uncertainty associated with the sensitivity of sectors to climate change. Of course, there are more uncertainties than just climate sensitivity in the integrated assessment model. There are concerns about the carbon cycle, the range of temperature changes, climate variance and extreme events, and the emissions path of carbon. All of these sources raise questions about the future values of the social cost of carbon. However, it is important to note, that these scientific sources of uncertainty have little sway on the impact of current emissions. Current carbon emissions increase carbon dioxide concentrations slightly above 370 ppm. The social cost of carbon today concerns what happens if the concentrations rise to 371 ppm. At these low levels of concentrations, there is less scientific uncertainty about what will happen. The primary source of uncertainty is the climate sensitivity of each sector. Consequently, the social cost of carbon for the next few decades is not that uncertain. It is very likely to be quite low and possibly even beneficial.

V. Policy Conclusion

This study has examined the social cost of carbon and explained why the concept is so important to carbon policy. The social cost of carbon should reflect the present value of the stream of global damages that a ton of emission causes far into the future. The estimate should serve as a ceiling over which marginal costs of mitigation should not rise. That is, firms and people should be exempt from any control regulation that exceeds the social cost of carbon. It is consequently an extremely important number and not one to be taken lightly.

The paper also makes it clear that estimating the social cost of carbon is difficult. It requires an immense body of scientific literature be organized in a structured way to determine the consequences of carbon emissions. This body of information must extend across the entire globe. Further, the analysis must peer into the distant future. The social cost of carbon will always be uncertain.

Despite these problems, the literature has steadfastly moved forward and calculated bold estimates. Starting with the seminal research of Nordhaus (1991), a host of models have subsequently been built to measure this value. Pearce et al (1996) led a noble effort to summarize this literature for the Second Assessment Report. A comparable value is notably missing in the Third Assessment Report. A range of \$7 to \$20 per ton was considered plausible given the information at the time.

More recently, the UK Government released its own estimate of the social cost of carbon (Clarkson and Deyes, 2002). This document is based heavily on an earlier EU document (Eyre et al. 1997). Assuming a social discount rate of 3%, the EU document recommends estimates of the social cost of carbon in the neighborhood of \$20 per ton. This is on the high side of the old numbers. Under the same conditions, the UK study doubles this value to \$40 per ton. The UK study goes even further in arguing for a 1% discount rate that would support a \$100 per ton estimate. Although both of these studies may be very helpful in justifying aggressive carbon policies, these values cannot be justified by what we understand about impacts. The criticisms levelled by Pearce (2003) concerning the UK report are warranted.

First, one cannot choose a different discount rate simply because one is studying climate change. Discount rates measure the value of time. The value of time is the same whether the UK is investing in new railroads, industrial facilities, education, or greenhouse warming. If the country is using a 3% real rate for its other public investments, it cannot opt for a lower rate for this sector alone. Further, the private market is offering effectively a 4% real rate of return. Money that is taken from private investment and diverted to carbon mitigation will be replacing a stream of income that earns 4%. A good case can consequently be made that the social discount rate ought to be 3%. The higher social cost of carbon estimates obtained from using a 1% discount rate cannot be justified.

Second, the UK study attempts to double the magnitude of the impacts because the damages fall heavily on people in poor nations. The new literature confirms that the impacts fall heavily on poor countries whereas wealthier nations largely benefit. However, contrary to Azar (1999) and a number of other authors who have explored income-weighting schemes, one cannot simply multiply the harmful impacts to poor nations by some arbitrary factor in cost benefit analysis. Multiplying the damages of poor people in an analysis does not make them better off. If the UK is concerned with the uneven income distribution in the world, they should fund a substantial development package to these poor countries as compensation for the damages. A compensation package would offer \$1 of benefits instead of some arbitrary fraction of a dollar for every \$1 spent. There is little doubt that the poor nations of the world would rather have compensation today than an extensive carbon control program. A carefully designed development package could help these poor nations develop more robust economies that would make them less vulnerable to climate change. Including a health component in that package could save more lives today than will ever be lost from climate change. If the income distribution is the problem, the answer is a global warming compensation program not an overenthusiastic mitigation program. Carbon mitigation is a very poor substitute for organized compensation.

Third, more recent research suggests that previous damage estimates are far too high. The new impact research has identified that warming will be beneficial as well as harmful, especially for low concentrations of carbon dioxide. The new research has revealed that adaptation, which was largely ignored in the earlier literature, is quite important. In net, the global damages from warming appear to be about an order of magnitude smaller than was previously thought. Although a great deal of uncertainty still remains about these estimates, the expected value of damages is considerably smaller. These results imply that the social cost of carbon is currently about \$1-\$2 per ton. Although it will rise over time as carbon accumulates, there is every reason to expect that the social cost of carbon will remain below \$10 per ton for the next 30 years.

There is a great deal of uncertainty surrounding global warming and its long term impacts. However, decisions in the near term only concern near term emissions. The consequence of releasing emissions for the next few decades is to increase greenhouse gas concentrations only slightly above what they are currently. This is expected to have only a small effect on temperature and thus only a limited impact. The uncertainty about the social cost of today's emissions is not that great. The uncertainty of concern is with future emissions. The social cost of carbon for emissions beyond 2050 is large. This, however, does not imply that the uncertainty surrounding the social cost of carbon now is high. The primary source of uncertainty in the near term is the sensitivity of sectors to climate change. Even this is likely to be small for small changes in temperature.

These results clearly have implications for UK and global mitigation plans. The results suggest that only inexpensive mitigation efforts need be undertaken in the near future. If future outcomes reveal higher values, mitigation efforts can be increased. However, for the time being, carbon mitigation should not cost more than a few dollars per ton. The UK should examine its own policies very closely. The UK is clearly free to spend up to \$100 per ton controlling carbon emissions. However, if the rest of the world stops at \$5 per ton or less, the UK will find itself buying some very expensive mitigation that will have only a negligible effect on the global climate. It will be barely possible to even detect what this extra sacrifice has done to improve the climate much less to notice the change. It simply is not effective for a single country to unilaterally control emissions more than the rest of the world.

Viewed from another perspective, the low social cost of carbon is a blessing for policy makers responsible for carbon control. The results suggest that there is time for efficient programs to be designed for the future. Crash programs that impose very high burdens can be avoided for the time being. Negotiators have time to work out international agreements. Countries have time to experiment with alternative control approaches. There is time to find effective long term solutions.

The results also suggest there should be more to greenhouse gas policy than mitigation. In the near term, the developed world needs to seriously consider a compensation package targeted at the low latitude countries. The inequities of the greenhouse gas problem in the near term are striking with wealthy countries doing most of the emissions and enjoying likely benefits. Something must be done to compensate low latitude countries for their likely damages. The impact results strongly hint that a compensation package could address the serious imbalance of impacts and make everyone better off. Even a small compensation package today would provide welcome relief for low latitude countries.

In the long run, the results also suggest that every country must pay attention to adaptation. The world's climate will change. Some adaptation will come naturally. However, some adaptation requires forethought by the government. It is not too early for governments to begin planning for climate contingencies.

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