Damage Estimates and the Social Cost of Carbon: The Need for Change

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One-page summary:

The social cost of carbon (SCC) is a measure of the damage caused by an incremental ton of CO_2 emissions. It was estimated at $21 per ton of CO_2 by an interagency working group in 2009. The working group relied on three models which assume quite low, or even negative, damages from the first several degrees of warming; this choice biases the SCC estimates downward.

The problem is not limited to the modeling of catastrophic risks and impacts at relatively high temperatures; these important issues are addressed in the work of Martin Weitzman, among others. There also are serious problems with the treatment of the damages from the first few degrees of warming, which dominate the results of short-run and high-discount-rate analyses.

FUND projects net global benefits from the first 3^{o}C of warming. (Hence, at a 5% discount rate, FUND finds the SCC to be negative, implying that carbon emissions should be subsidized.) FUND's net benefits from warming emerge primarily from two areas. First, it relies on dated and overly optimistic research on agricultural impacts. Newer research implies much lower, if any, agricultural benefits from warming. Second, FUND projects a huge reduction in mortality from warming, mainly due to the arbitrary assumption that rural populations suffer from cold-related deaths, but not from heat-related deaths. FUND values avoided deaths at 200 times per capita incomes, so this assumed mortality reduction leads to a large monetized benefit.

DICE projects very small net damages from the first few degrees of warming. DICE assumes, on slim evidence, that there is a large global willingness to pay for the enjoyment of warmer weather. This category, which is not included in most analyses, offsets much of the economic damages from warming, which are assumed to be small. Michael Hanemann (2008) reviews each component of the DICE damage function in detail, and produces a revised total which is four times as large as assumed in DICE.

PAGE damage estimates are indirectly calibrated on the basis of past studies by Nordhaus and Tol; they do not represent independent research on climate damages. As PAGE developer Chris Hope and I, with other colleagues, have shown, the low damage estimates in PAGE2002 are due, in part, to the assumption of extensive, very low-cost adaptation; other reasonable hypotheses imply much greater damages (Ackerman et al. 2009).

In short, the pictures of climate damages relied on in the interagency working group's SCC estimate are fundamentally at odds with the mainstream of recent climate science and policy discussion, including the widely accepted importance of staying below 2^{o}C of warming. Different damage functions – likely implying a much higher SCC – would be needed to incorporate the latest findings of climate science.

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Introduction: The importance of damage estimates

The estimation of the SCC, in the working group's analysis, is a complex endeavor with multiple stages. In some respects, such as the treatment of uncertainty in the climate sensitivity parameter, the working group provides a thorough analysis that is grounded in recent scientific research. The climate sensitivity parameter alone, however, does not determine the SCC. Climate sensitivity governs the relationship between greenhouse gas concentrations and temperature; estimates of damages (the damage function, for short) express the relationship between temperature and economic impacts.

In the area of damage estimates, the working group relied on the damage functions used by three existing models, FUND, DICE, and PAGE, with no changes and virtually no review of the issues at stake. This was not forced on them by the structure of their analysis; in other respects, the working group showed an impressive ability and willingness to take apart the models and "mix and match" features and assumptions from a variety of sources. The SCC estimates are based on runs of FUND, DICE, and PAGE, modified to incorporate emissions and economic growth scenarios from five other models, and a completely new Monte Carlo analysis of climate sensitivity. It is equally possible, and equally important, to evaluate the damage functions and consider the need for a new analysis in this area.

The underestimation of damages is most extreme in FUND, which projects net benefits to the world from the first 3^{o}C of warming. In the working group report, it is clear that FUND yields lower estimates of the SCC than the other two models. Indeed, among the working group's 45 SCC estimates – reflecting all combinations of 3 discount rates, 3 models, and 5 baseline scenarios – the estimates generated with FUND are, on average, lower than the estimates from the other two models by $21 per ton of CO_2 (a difference which is coincidentally equal to the estimated SCC).

The damage functions in all three models rely on dated and, at times, idiosyncratic analyses that generally paint a picture of climate change as a minor, inexpensive externality. They are incompatible with the picture of climate change as a fundamental threat to existing ecosystems, communities, and ways of life that is emerging from climate science. This memo identifies some of the priorities for improvement in modeling damages; many other issues in damage estimation should be addressed as well, in a thorough review of the problem. For other relevant comparisons of FUND, DICE, and PAGE, see Mastrandrea (2009) and Warren et al. (2006).

There are four major sections to these notes. The first two address agricultural impacts and health impacts in FUND. The following sections examine damage estimates in DICE, and damage estimates in PAGE. A short postscript offers completely speculative implications for the SCC.

Agricultural impacts in FUND

The latest available technical description of FUND is Anthoff and Tol (2008), describing FUND version 3.3. Its description of agricultural impacts appears to be unchanged from earlier versions, and is based on Tol's 2002 analysis (Tol 2002a, b), which projects net benefits for agriculture worldwide from the next 180 years of climate change (see Tol 2002b, Figure 1).

There are three components to the impacts of climate change on agriculture in FUND, each calculated separately by region and time period. The first is a small negative term which is proportional to the rate of temperature change, based on the assumption that it is harder for farmers to adapt to more rapid change.

The second term assumes that each region has a fixed optimal temperature for agriculture, which is between 0.70^{o}C and 1.51^{o}C above 1990 levels for 13 of the model's 16 regions; for the United States it is 1.09^{o}C above 1990 (Anthoff and Tol 2008 tables). Temperature increases have a positive impact on agriculture until the optimum is reached, and a negative impact thereafter.

The third term models CO_2 fertilization, assuming that the percent change in agricultural production is proportional to the logarithm of the atmospheric concentration of CO_2. This implies that every doubling of CO_2 concentrations has the same positive effect on agriculture, independent of temperature effects.

According to Anthoff and Tol (2008), these equations are calibrated to the results of economic analyses of agriculture published between 1992 and 1996. More recent and detailed research on agriculture paints a much more pessimistic picture of the likely effects of climate change. (An important error in some earlier studies, stemming from the failure to distinguish between irrigated and rain-fed agriculture, is explained in Schlenker et al. 2005). Many studies use a Ricardian approach, in which the value of farmland is interpreted as a proxy for the present value of future farm profits.

For instance, Schlenker et al. (2006) estimate that U.S. farmland east of the 100th meridian will lose 11 to 25 percent of its value by mid-century, and 27 to 69 percent of its value by the end of this century, under standard IPCC climate scenarios. Most of the loss is attributable to the expected increase in degree-days above 34^{o}C, a temperature which is harmful to most crops, rather than to changes in average temperatures. A companion article on the value of farmland in California (Schlenker et al. 2007), the principal agricultural area west of the 100th meridian, highlights the importance of water for irrigation. Climate scenarios that imply reduced availability of water will cause substantial losses in California agriculture.

A different view of climate impacts on U.S. agriculture is presented by Deschênes and Greenstone (2007); their central estimate is that climate change will increase farm profits by $1.3 billion, or 4 percent, by the end of the century. However, a recent re-analysis of the Deschênes and Greenstone result (Fisher et al. 2010) claims that there are serious deficiencies in their data and methodology, and that correction of these deficiencies leads to a projection of significant climate-related losses in agriculture.

These studies focus on the United States, rather than on worldwide agriculture. Many countries, however, are currently hotter and more water-stressed than the United States, and will likely face even more severe agricultural losses from climate change. A recent global study projects negative aggregate impacts on agriculture, and a decline in yields even with carbon fertilization, by the end of this century, with the worst impacts in developing countries (Cline 2007).

Biological research in the 1980s projected substantial yield increases from CO_2 fertilization, based on studies in enclosed areas such as greenhouses. These results were incorporated into economic analyses in the 1990s, such as the calibration of FUND. More recent biological research, however, has been conducted under more realistic, outdoor conditions (Long et al. 2006). This newer work has found much lower benefits from increased CO_2 levels, and some offsetting losses due to increases in ground-level ozone (which often results from the same fossil fuel combustion that increases CO_2). Other research has found that for many crops, CO_2 fertilization leads to faster growth in plant weight than in nutritional content – that is, it lowers nutrient density (Jablonski et al. 2002).

In short, FUND's estimates of the agricultural impacts of climate change should be recalibrated to reflect the harm done by an increasing number of very hot days, the risks of decreased water availability for irrigation, and the more limited expectations for CO_2 fertilization found in newer research. These changes would lower the projected benefits, or increase the damages, in agriculture from the early stages of climate change.

Human health impacts in FUND

As with agriculture, the treatment of human health impacts in the latest version of FUND (Anthoff and Tol 2008) is based on the earlier analysis by Tol (2002a; 2002b). That analysis concludes that "In the central case, climate change reduces mortality, peaking at half a million avoided deaths [per year] around 2050" (Tol 2002b, p. 154). Although FUND models the impacts of climate change on several diseases, almost all of the projected health impacts – and all of the avoided deaths – come from changes in cardiovascular and respiratory diseases.

Cardiovascular and respiratory disease mortality rates are closely correlated with short-term temperature fluctuations, especially among people over 65; increased deaths can be caused either by excessive heat or by excessive cold. Many studies have found a V-shaped relationship between daily mortality and daily temperatures (e.g. Martens 1998); the point of the V represents the minimum-mortality temperature. The left side of the graph is often more steeply sloped than the right; that is, the decline in cold-related mortality is faster than the increase in heat-related mortality, per degree of warming.

FUND uses such a relationship, with separate parameters for each region, and extrapolates inappropriately from it to project large reductions in mortality from warming. There are at least three problems with the treatment of temperature-related mortality in FUND. (This account is based on Ackerman and Stanton 2008.)

First, FUND makes the arbitrary and unsupported assumption that there are no heat-related cardiovascular deaths in rural areas. This assumption makes little difference for highly urbanized countries, but it introduces a serious bias into estimates for countries and regions with large rural populations. In rural China, India, and Africa (among other places), FUND assumes that warming reduces cold-related cardiovascular deaths but does not cause additional heat-related deaths. This assumption is mentioned only in passing, in a single sentence, both in Anthoff and Tol (2008) and in Tol (2002a), with no citations of supporting evidence.

Second, FUND assumes that the minimum-mortality temperature (MMT) remains constant over time in each region. It is much more likely that the MMT will adapt to gradual changes in local conditions. Cross-sectional evidence demonstrates that MMT is not the same everywhere. For instance, a study of 11 U.S. cities found the expected V-shaped relationship of mortality to temperature in 10 cases, with the MMT closely correlated to local temperatures; at the extremes, the MMT is 9^{o}C higher in Miami than in Chicago (Curriero et al. 2002). Since people move freely between Miami, Chicago, and elsewhere in the United States, the persistence of differences in the MMT correlated to local temperatures implies that migrants adapt to their new surroundings; otherwise, there would be regression toward a national mean MMT.

As temperatures gradually rise due to climate change, it seems likely that people will adapt, and the MMT will rise as well. Standard climate scenarios imply much less temperature change per human lifetime than is experienced when moving from Chicago to Miami. But if the MMT, and the whole V-shaped mortality-temperature relationship, move in parallel with gradually rising temperatures, then there is no basis for FUND's projected mortality reduction from warming.

Third, global warming implies not only gradual change in average temperatures, but also an increasing frequency of heat waves. FUND does not include mortality from heat waves, even though it is well documented that people do die from episodes of extreme heat. This category of deaths would be expected to increase as temperatures rise.

In short, zero would be a better estimate of the near-term impact of climate change on mortality, in place of FUND's projection of hundreds of thousands of lives saved annually. More careful research might identify other impacts, such as heat waves and other heat-related diseases, which should be included in a recalibration of the health effects of climate change.

Damage estimates in DICE

The latest version of DICE is documented in a recent book by Nordhaus, which estimates that under a business-as-usual scenario, climate damages would amount to just 2.5 percent of world output by the end of this century (Nordhaus 2008, p. 6). Additional documentation is available in the somewhat cryptic "lab notes" available on Nordhaus' website; these notes, and the recent book, make it clear that the approach to damages is little changed from the previous version of DICE, which is described in more detail in Nordhaus and Boyer (2000).

The most surprising feature of the DICE damage function is the inclusion of a large category of benefits of warming: the amenity value of non-market time use. In a 1998 study, Nordhaus examined a set of individual time use diaries for Americans in 1981, finding that time spent on outdoor recreation rises with temperature. From this he concluded that the amenity value of 2.5^{o}C of warming would amount to 0.3 percent of GDP for the United States, and that the positive amenity impact would be maximized at a temperature of about 20^{o}C (Nordhaus and Boyer 2000, p. 84). In the absence of other information, DICE applies this temperature standard worldwide (Nordhaus and Boyer 2000, p. 85).

Since the global average temperature is currently below 15^{o}C, DICE effectively assigns a positive value to the first 5^{o}C of warming, based on increased enjoyment of warm-weather recreation. The supposedly amenity-maximizing temperature of 20^{o}C is the historical average temperature of Houston and New Orleans (Ackerman and Finlayson 2006). In DICE, the subjective benefit of making the world as hot as Houston offsets other damages from the first 5^oC of warming.

Few other studies have followed DICE in monetizing the desirability of warmer weather. One study explored the link between climate and subjective well-being across 67 countries, finding that the moderate warming expected over the next 25 years will lead to increased happiness primarily in a few of the coldest, northernmost countries; most of the world will be unhappy with climate trends long before warming reaches 2.5^oC (Rehdanz and Maddison 2005).

Questions have also been raised about other aspects of the DICE damage function. Hanemann (2008) reviews DICE's sectoral damage estimates, as applied to the United States, and suggests revisions to many categories. Hanemann's revised total estimate of climate damages to the United States from 2.5^oC of warming is four times as large as the DICE estimate.

Damage estimates in PAGE

The PAGE model has been innovative in other areas, such as the application of Monte Carlo analysis to numerous aspects of its calculations, but has never developed detailed or independent estimates of damages. Its first version used an aggregate damage function for each region of the world, benchmarked to match available economic research (Hope et al. 1993). That structure has remained in place in later versions: PAGE2002 does not address sectoral damages; instead, it benchmarks its aggregate damage functions to the 2001 IPCC report – specifically, to a section of that report which presents damage estimates from Tol, Nordhaus and Boyer, and Mendelsohn (Hope 2006; citing IPCC 2001, Working Group II, p. 940).

The working group's very similar SCC estimates from DICE and PAGE, therefore, do not represent two entirely independent evaluations of climate damages. PAGE acknowledges the dependence of its default data on DICE, and obtains similar results.

In a recent article, PAGE developer Chris Hope and I, with two other colleagues, explored the reasons for the relatively low PAGE2002 estimates of climate damages for the United States and the world (Ackerman et al. 2009). By default, PAGE2002 assumes very extensive, very low-cost adaptation, especially in high-income countries; it only reports damages net of that adaptation. Moreover, its assumptions about catastrophic losses seem to have lagged behind current scientific research on climate risks. Making several reasonable data modifications, we created alternative scenarios with damages up to 4 to 6 times as large as the PAGE2002 defaults.

Postscript: Speculation on possible implications for the SCC

The working group's SCC estimate of $21 per ton of CO_2 rises to $29 if FUND is excluded on grounds of unreasonable damage estimates. Both the Hanemann re-evaluation of DICE and the Ackerman-Hope alternative scenarios for PAGE2002 suggest that damages could be four times as large as the models' defaults. If the same percentage increase applies to the SCC, it rises to $84 for all three models, or $112 if FUND is excluded.

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