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Short communication

A critique of climate damage modeling: Carbon fertilization, adaptation, and the limits of FUND

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ABSTRACT

Among the climate economics models widely used in policy analysis, FUND is unique in several respects, including its disaggregated, modular treatment of damages and its relatively low estimates of damages and the social cost of carbon (SCC). We present two possible reasons for FUND's low damage estimates: the representation of carbon fertilization in agriculture; and assumptions about the extent of adaptation.

We explore these issues in FUND 3.8, comparing the model's default results to scenarios without carbon fertilization and adaptation. We find that carbon fertilization is projected to provide a large net benefit, offsetting many of the damages in other categories; almost half of this benefit occurs in China, based on FUND's assumptions about the regional strength of carbon fertilization. Automatic adaptation, tied to increases in per capita income, reduces many damages, particularly deaths caused by climate change; almost three-fourths of the reduction in climate-linked deaths is projected to occur in sub-Saharan Africa. Moreover, many categories of damages are surprisingly small, a topic that warrants further research. As long as FUND's default forecasts remain significant in climate policy debate, it is important to understand the sources of FUND's low estimates of climate damages.

1. Introduction

The integrated assessment models (IAMs) of climate economics have become important in climate policy debates. Projections of costs and benefits of climate mitigation, leading to estimates of the "social cost of carbon" (SCC, the marginal damages from a ton of CO_2 emissions), are often derived from IAM analyses. As a result, it is important to understand the logic of these models, and the ways in which they agree or disagree.

Although many IAMs appear in the academic literature, three relatively simple ones, DICE, PAGE and FUND, have received widespread attention. In addition to their use as research tools, they form the basis for the U.S. government's SCC estimates, which are averages of the results of DICE, PAGE and FUND when applied to the same set of scenarios.[1] Of the three models, FUND is the most complex and the least transparent; this article explores the sources of FUND's SCC estimates.

The performance of a range of IAMs has been evaluated on many dimensions, including the representation of physical outcomes such as the carbon cycle, atmospheric and climate dynamics [6,13]. In the crucial area of climate damages, however, the diverse approaches to modeling climate damages adopted in IAMs are hypotheses about future economic, biological and physical impacts of temperatures outside the range of human experience. Several authors have emphasized both the importance and the weakness of IAM assumptions about climate damages [5,7,10,14].

The three models are structured quite differently. DICE, the best-known and most widely used IAM, is also the simplest. A system of 19 major equations represents, in skeletal form, all the interacting dynamics of the global economic and climate systems. PAGE, developed for European Union climate analyses and used in the Stern Review, is only moderately more complex. In particular, both DICE and PAGE use highly aggregated representations of climate damages: in DICE, a single equation projects aggregate worldwide damage costs as a function of temperature; in PAGE, a small number

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[1] References to publications presenting the DICE, PAGE and FUND models can be found in the US government SCC analyses. For the 2010 analysis, see http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf. For the 2013 version, including technical corrections through July 2015, see https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf.

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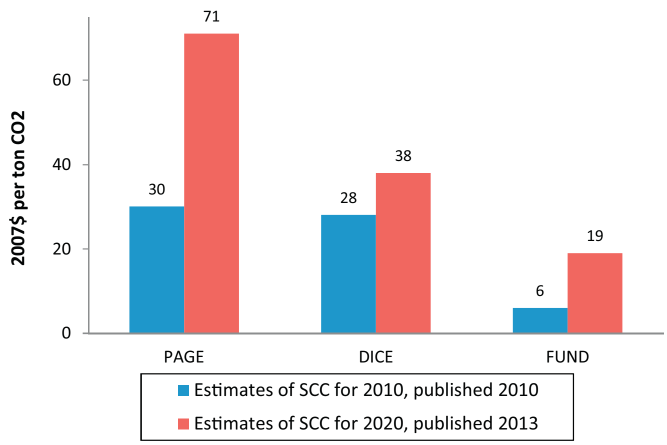

Fig. 1. US government's SCC estimates from PAGE, DICE and FUND. (For interpretation of the references to color in the text, the reader is referred to the web version of this article).
Sources: see note 1.

of damage categories (though differentiated by region) each have comparably simple dynamics.

FUND offers a disaggregated treatment of climate damages, modeling 15 major categories, some of them including separate equations for multiple subcategories. Most of the model's technical description is devoted to presenting these damage categories and their equations, although little is said about the logic of the algorithms in several categories. Our goal is to provide an outside evaluation of FUND's inner workings, to help provide a basis for judging the reliability of the model and the need, if any, for changes.

We sought, in an earlier study [1], to disaggregate the results of FUND in order to better understand them. The designers of FUND criticized our code alterations; in their view, even a one-line change to existing code, intended solely to allow sensitivity analysis, was invasive to the integrity of the model [2]. The current study presents an assessment of FUND in which no changes are made in the code; our new sensitivity analyses are based solely on varying the input parameters.

2. A tale of three models

The differences among the three models' SCC estimates are shown in Fig. 1. The blue (left-hand) bars represent values for 2010 emissions, published in 2010. The red (right-hand) bars are estimates for 2020 emissions, from the 2013 revision of the US SCC.[2] The U.S. government estimate of the SCC is the average of the three individual model values. For the 2010 values shown here, the three-model average was $21/tCO_2$; the two-model average of DICE and PAGE was $29. The 2020 values shown here are substantially higher, reflecting both the projection of worsening climate conditions over time, and revisions in all three models. In this case the three-model average was $43; the two-model average of PAGE and DICE was $54. Thus the inclusion of FUND, in both cases, reduced the U.S. government SCC more than 20% below the average of the other two models.

In our earlier study [1], we demonstrated that if FUND 3.5 substituted the DICE damage function in place of FUND's own damage calculations, FUND's estimate of the SCC would be very close to the DICE value. This suggested that FUND's damage calculations are crucial to the difference between the models. That article [1] explored several aspects of FUND, but became known primarily for its identification of an algebraic defect in FUND 3.5; the defect is absent from FUND 3.6 and later versions.

The current study addresses an overlapping though not identical set of issues about the modeling of damages, with calculations based on FUND 3.8 (the latest available at the time of our analysis). The analysis and calculations described here are based on the FUND 3.8 software exactly as downloaded, without modification.[3]

Why are the SCC estimates from FUND so low? We explore two possibilities, involving the treatment of carbon fertilization, and assumptions about adaptation. While we are interested in explaining the differences between FUND and other models, we are not offering judgments about the correct value of sectoral damages, or of the SCC. Those important topics are beyond the scope of this analysis.

3. Carbon fertilization

Plants grow by absorbing CO_2 from the atmosphere; the availability of CO_2 is in some (not all) cases a limiting factor on plant growth. All else being equal, an increase in atmospheric concentration of CO_2 could act as a fertilizer, boosting farm and forest yields. While this effect is well known, its magnitude is less certain. Current documentation indicates that FUND still relies on early, very high estimates of carbon fertilization effects, thereby modeling a large apparent benefit of climate change.

FUND's parameters for estimation of agricultural impacts are, according to the technical documentation for version 3.8, calibrated to the results of five studies published between 1992 and 1996 (FUND 3.8 Scientific Documentation, 7; see also [11]). FUND assumes that climate change has three additive effects on agricultural output; one of these is carbon fertilization, which is always a net benefit. The other two effects, which reflect the level and rate of change of temperature, are usually net costs—but they are often smaller than carbon fertilization, resulting in an overall net benefit from climate change in agriculture. With simplified notation, the equation for carbon fertilization (FUND 3.8 Scientific Documentation, equation A.4) is:

$$A_{t,\mathrm{r}} = k_{\mathrm{r}} 1\mathrm{n}\left(\frac{CO_{2t}}{275}\right) \quad (1)$$

A is the percentage change in agricultural output due to carbon fertilization at time t in region r, CO_{2t} is the atmospheric concentration of CO_2 at time t in ppm, and 275 is the pre-industrial concentration. The values of k_{r}, which determine the strength of the carbon fertilization effect for each region, are derived by comparing results from the 1990s studies with and without carbon fertilization.

Research since the mid-1990s has substantially expanded the understanding of carbon fertilization. It is difficult to pin down precise impacts on yields due to nonlinear interactions of carbon fertilization with precipitation, nitrogen, and ground-level ozone [3,4,8]. For example, fossil fuel combustion emits both CO_2, promoting plant growth, and precursors of ozone, which impedes plant growth; the net effect on crop yields is ambiguous. Few studies have incorporated the effects on weeds, which may have a stronger response to CO_2 fertilization than useful crops [9].

In view of such uncertainty and complex interactions, FUND's modeling strategy – incorporating a substantial estimate of one positive effect of climate change, without comparable estimates

[2] The 2010 SCC analysis included details on the estimates from the three models for 2010; the 2013 revision included comparable details only on its estimates for 2020. These estimates are based on a 3% discount rate and a climate sensitivity parameter of 3; although other estimates were published in both years, these are the most widely used. The climate sensitivity parameter is the long-run global average warming projected to result from a doubling of atmospheric CO_2, measured in $^{\circ}$C. FUND estimates used in the SCC analysis do not include equity weighting.

[3] FUND software, documentation, and data tables (inputs), for all versions, are available at http://www.fund-model.org/.

Table 1
Income elasticities in FUND 3.8.

Category	FUND 3.8 defaults	Impact when per capita GDP doubles	No-adaptation alternative
Agriculture share of GDP	−0.31	0.81	0
Forestry share of GDP	−0.31	0.81	0
Water resources	0.85	1.80	1
Space heating	0.80	1.74	1
Space cooling	0.80	1.74	1
Diarrhea mortality	−1.58	0.33	0
Diarrhea morbidity	−0.42	0.75	0
Vector-borne disease	−2.65	0.16	0
Tropical storm damages	−0.51	0.70	1
Tropical storm mortality	−0.50	0.71	0
Non-tropical storm damages	−0.51	0.70	1
Non-tropical storm mortality	−0.50	0.71	0
Dryland values	1.00	2.00	1
Wetland values	1.16	2.23	1
Value of statistical life	1.00	2.00	1
Value of year of morbidity	1.00	2.00	1

of negative factors such as the effects of increased ground-level ozone or more rapid weed growth – could lead to biased estimates of the overall impact on agriculture. Based on more recent research, a better modeling strategy would estimate the joint impact of multiple effects of climate change on yields. Due to the importance of nonlinear interactions, the changes in yields cannot be accurately expressed as the sum of several independent, single-factor effects, as FUND assumes at present.

4. Assumptions about adaptation

FUND projects, as do many IAMs, that there will be a robust rate of economic growth in the future, barely affected by the early stages of climate change. It further assumes that higher-income countries suffer proportionately less from climate change, or can adapt more successfully to climate impacts. Unlike DICE and PAGE, however, FUND makes specific adjustments based on per capita incomes throughout its damage calculations, automatically reducing impacts as incomes rise. These changes in impacts are expressed as income elasticities—the percent change in impacts associated with a one percent change in per capita income. That is, many of the equations for damages have the general form:

$$\text{Impact}_{t,\text{r}} = f(z)\left(\frac{y_{t,\text{r}}}{y_{0,\text{r}}}\right)^{\varepsilon} \quad (2)$$

Here y is per capita income at time t in region r, ε is the elasticity, and z is a set of other variables that influence the magnitude of impacts.

Income elasticities found in the FUND 3.8 technical documentation are shown in the first column of Table 1. A negative elasticity implies an absolute decline as GDP per capita rises; an elasticity between 0 and 1 implies that a variable grows with income, but more slowly than GDP per capita, hence declining in relative importance. For an elasticity of ε, the "impact" column of Table 1 shows 2^{ε}: for example, a doubling of per capita GDP reduces the share of agriculture in GDP to 81% of its previous value, and reduces impacts of vector-borne diseases (such as malaria) to 16% of their previous level.

Of the 15 variables shown in the table, only the value of wetlands is assumed to grow faster than per capita income. The values of dry land, avoided deaths and avoided morbidity are assumed to be proportional to GDP per capita. The other 11 variables all decline, either absolutely or relatively, when GDP per capita rises.

In short, FUND assumes that numerous types of climate impacts become progressively less severe as the world becomes richer. Agriculture, forestry, water resources, heating and cooling costs, health impacts, and storm damages all tend to shrink in importance as incomes rise, declining either in absolute terms or as proportions of GDP.

The table also presents a "no-adaptation alternative" for each category, used in our scenario analysis below. The alternative elasticity is 0 for shares of GDP and for physical quantities and rates, holding these constant regardless of changes in per capita income. For example, the no-adaptation alternative assumes no change in the share of GDP from agriculture. The alternative elasticity is 1 for monetary amounts, assuming that they grow in proportion to per capita income; thus the value of storm damages is assumed to grow at the same rate as per capita income.

Richer countries undoubtedly have greater ability to adapt to climate change. But high incomes do not automatically lead to successful adaptation, as shown by the inadequate and ill-prepared response of the United States to Hurricane Katrina in 2005 and Hurricane Sandy in 2012, or the similarly feckless response of European countries to the devastating heat wave of 2003. Each of these cases resulted in immensely expensive, largely avoidable climate damages. These episodes, of course, do not imply a specific value for income elasticities; but they do provide a caution about assuming that higher income always leads to adaptation. If FUND has overstated the link between income and adaptation, then it may be underestimating future damages (net of adaptation).

The modeling approach used in FUND also assumes the same relative strength of adaptation applies at all temperatures, high and low. Are there limits to adaptation, such as temperatures and impacts great enough to overwhelm any attempts at adaptation? If so, then an appropriate modeling strategy would assume no additional adaptation once a temperature threshold has been reached. FUND has no such upper limits, and therefore may be modeling more high-temperature adaptation than is physically plausible.

5. Methods

We compared results from four scenarios, running them in FUND's "best guess" mode. The best guess mode is so named because it turns off FUND's numerous Monte Carlo variables, using the best single estimate (the mode of the assumed distribution) in each case. This involves a tradeoff: in Monte Carlo mode, FUND allows many of its input parameters to vary, providing a form of sensitivity analysis; on the other hand, the resulting variation in outputs is difficult to interpret, both because there are literally dozens of Monte Carlo parameters in the model, and because disaggregation of the Monte Carlo results by sector or region becomes unwieldy.[4] In best guess mode, FUND produces a manageable amount of detailed information on the components of the present value of global climate damages from an incremental ton of emissions. These components are disaggregated by damage category, region, and year in which the damages occur, calculated under any of six assumptions about discounting.

Our four scenarios are as follows:

- The Base Case scenario uses the FUND 3.8 default data set, without modification. The other scenarios use the same inputs except as noted.

[4] FUND's full, disaggregated output offers all the detail included in the best-guess output, for each of the Monte Carlo iterations. A best-guess output file contains 432,000 lines, so the full output from one 10,000-run Monte Carlo analysis would contain 4.3 billion lines of results. We did not produce or analyze a full, disaggregated FUND output from a Monte Carlo analysis.

- The No Fertilize scenario turns off carbon fertilization, by setting k_r in Eq. (1) to zero for all regions. As a result, the change in yield due to carbon fertilization is zero for all times and regions.
- The No Adapt scenario turns off the elasticity effects listed in Table 1, using the values shown in the final column of that table. The elasticity is set to one for monetary values of damages, making them proportional to GDP per capita; it is set to zero for shares of GDP and rates of mortality, morbidity, and specific diseases, making them independent of GDP per capita.
- The No Fertilize or Adapt scenario combines the assumptions of the No Fertilize and No Adapt scenarios.

These are intended to be analytically useful, not necessarily realistic, scenarios. By turning off all carbon fertilization and automatic adaptation in FUND, we are seeking to highlight their overall effects on the model when they are turned on. A realistic picture of the world would no doubt include some carbon fertilization and income elasticity effects, though not necessarily of the same magnitude as proposed in FUND.

Monetary estimates of damages and of the SCC are reported in US$/tC (1995 dollars), the standard reporting unit of FUND 3.8. To convert to more recent units, note that \$1.00/tC (1995 dollars) = \$1.56/tC (2014 dollars) = \$0.425/tCO_2 (2014 dollars).

6. Results

FUND results present six approaches to discounting, at rates of zero, one percent, or three percent,[5] with or without equity weighting (giving greater weight to impacts on low-income regions). For a ton of CO_2 emitted in 2005, the best-guess estimates of the SCC are shown in Table 2. The Table confirms the well-known result that the discount rate is of paramount importance in determining the present value of climate damages. In brief, a low discount rate raises the present value of damages because damages typically grow over time, becoming much larger in the later years of a scenario. Similarly, equity weighting raises the present value of global damages because lower-income regions typically suffer disproportionately larger damages.

Despite the central role of the discount rate, our focus is on the other determinants of the SCC at any given discount rate. The table shows that turning off either carbon fertilization or automatic adaptation causes a dramatic jump in FUND's estimate of the SCC. Carbon fertilization has a larger effect than adaptation at a three percent discount rate, while the reverse is true at a one percent or zero discount rate. Turning off both features has, unsurprisingly, a larger effect than either of them alone.

FUND calculates the SCC by estimating the incremental damages attributable to an increment in one year's emissions, over the 300 years following the emissions. The present value of the incremental damages is reported by year of damages, economic sector or damage category, and region of the world. To simplify the presentation, we will focus on one of the discounting options, the three percent rate with equity weighting; this may be the preferred option of FUND's developers.[6] Qualitatively similar patterns would be seen with any of the discounting options.

While there are calculations for 15 damage categories in FUND, only three of them are large in the outputs we examined: impacts on agriculture; costs of cooling (increased costs for air conditioning in a warmer world); and the value of deaths caused by climate-linked diseases. FUND values each premature death at 200 times regional per capita income; the global inequity introduced by this assumption is one reason to consider equity weighting of results.

Fig. 2 displays these components of the SCC for our four scenarios, showing present-value contributions to the SCC by damage year and sector. The overall SCC is the sum of the areas under all of the lines shown in a graph. Negative values, as seen for agriculture in two of the graphs, represent benefits. Although the scenarios extend over three centuries, only the first half of that time span is shown here; the present-value contribution of damages after 2150 is very close to zero at the three percent discount rate (this is not always the case at lower discount rates).

One of our results recalls the mystery of the dog that did not bark in the night: 12 of the 15 damage categories in FUND contribute roughly nothing to the SCC, as shown by the dashed line for "all other" impacts. These include storms, sea level rise, water resource problems, extinction of species, and other categories of impacts that would bark quite audibly in some accounts of climate damages.[7]

In FUND's view, the increased cost of air conditioning is the largest category of climate damages. Without cooling costs, the base case estimate of the SCC would be a negative \$10/tC—that is, a net benefit of \$10 from every ton of carbon emissions. This reflects both the large estimate of air conditioning costs and the small estimates of other damages.

Other results can be seen by comparing graphs in Fig. 2. The effect of carbon fertilization – compare left to right, i.e., 2a vs. 2b, or 2c vs. 2d – is a huge net benefit, reaching a sharp peak early in the period of analysis. In the absence of carbon fertilization (see 2b and 2d), the other effects of climate on agriculture lead to net costs.

The effect of adaptation – compare top to bottom, i.e., 2a vs. 2c, or 2b vs. 2d – is less dramatic, but also important. Adaptation, present in 2a and 2b, shrinks the value of impacts in agriculture and, even more, the value of climate-related deaths. The shape of the adaptation effect is smoother, with a later peak, compared to the early spike in carbon fertilization. This difference in timing occurs because carbon fertilization is proportional to atmospheric concentration of CO_2 (see Eq. (1)), while most other damage categories are assumed to be based on temperature, which rises more gradually after the modeled 2005 increase in emissions.[8]

Overall impacts on the SCC by sector and scenario are summarized in Table 3. Although carbon fertilization has small, indirect effects on other sectors, more than 99% of its effect is in agriculture. It decreases the SCC by \$19.4/tC with adaptation (compare Base Case to No Fertilize), or by \$29.3/tC without adaptation (compare No Adapt to No Adapt or Fertilize).

Adaptation affects all three major sectors, with the largest effect on the value of climate-related deaths. Across all sectors, adaptation assumptions in FUND reduce the SCC by \$11.9/tC with carbon fertilization (compare Base Case to No Adapt), or by \$21.8/tC without carbon fertilization (compare No Fertilize to No Adapt or Fertilize).

All of these effects are several times larger than the Base Case SCC of \$2.8/tC, emphasizing the importance of FUND's assumptions about both carbon fertilization and adaptation.

All of the impact categories in FUND can be disaggregated by region. For carbon fertilization, defined as the difference between the Base Case and No Fertilize scenario results, almost half (47.7%)

[5] These are rates of pure time preference, or equivalently the discount rates that apply to utility, rather than to monetary amounts.

[6] See the argument in favor of a three percent rate in Ref. [12], and several recent publications on equity weighting by David Anthoff and Richard Tol.

[7] The "all other" totals in Fig. 2 include a small benefit from reduced heating bills in a warmer climate (less than 14% as large as the increased cost of cooling), almost exactly offsetting the small net damages in the remaining categories.

[8] The SCC calculation is based on the effects of an incremental increase in emissions in the base year, 2005. This leads to a rapid increase in atmospheric concentration; some but not all of the additional CO_2 is then removed from the atmosphere fairly quickly, causing a spike in impact categories that are proportional to atmospheric concentration, such as carbon fertilization. Temperature has a smoothed and lagged response to atmospheric concentration, as seen in the shape of most other categories, which are proportional to temperature.

Table 2
FUND SCC for 2005 emissions (1995 $/tC).

Discounting	Base Case	No Fertilize	No Adapt	No Adapt or Fertilize
With equity weighting				
0%	217.0	297.4	669.8	785.7
1%	50.9	92.2	154.1	219.1
3%	2.8	22.2	14.7	44.0
No equity weighting				
0%	82.3	112.5	184.5	224.4
1%	19.0	35.2	41.5	64.0
3%	0.9	8.6	3.1	13.5

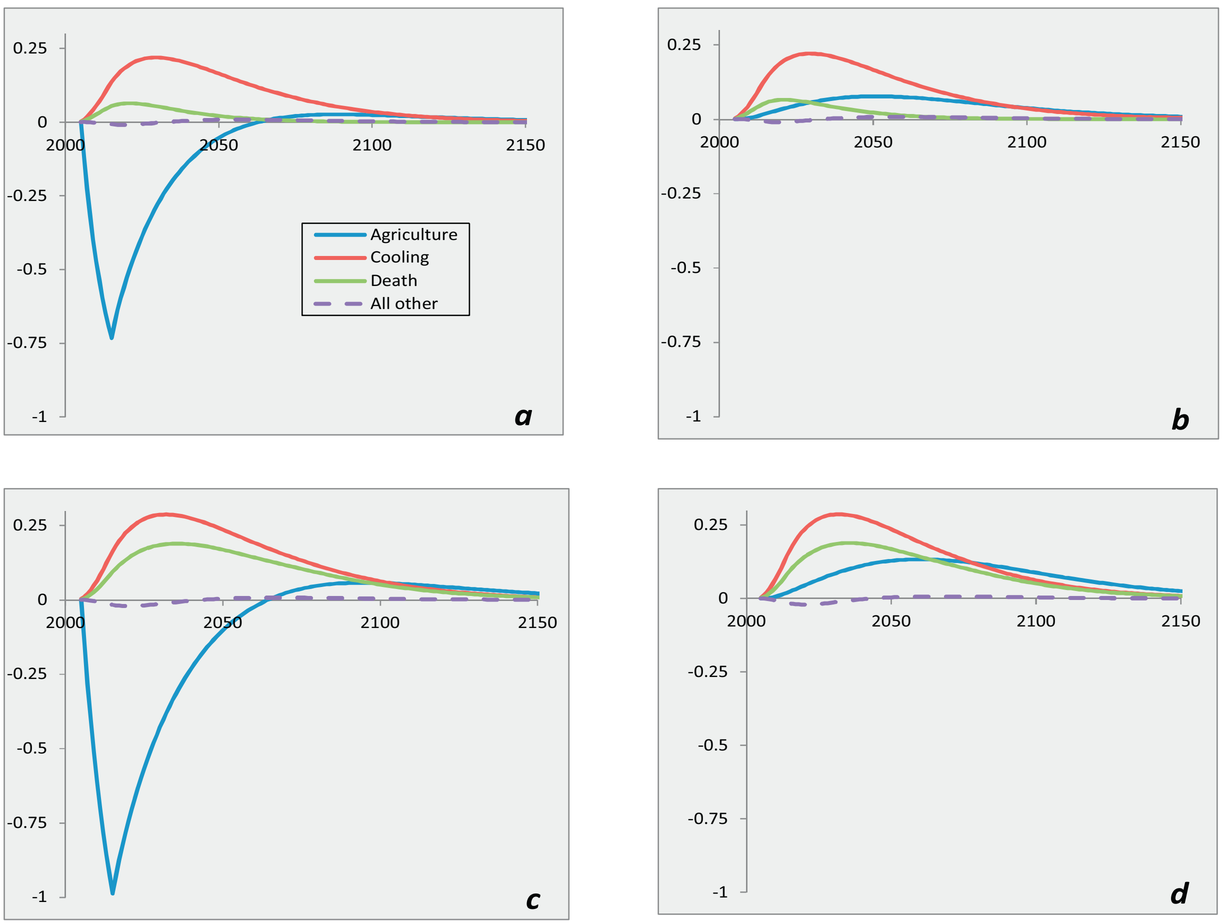

Fig. 2. SCC components (present values in 1995 US$/tC) by sector and year of damages.
(a) Base Case; (b) No Fertilize; (c) No Adapt; (d) No Adapt or Fertilize. (Negative values are benefits).

Table 3
Components of SCC (in 1995$/tC) by scenario.

	Base Case	No Fertilize	No Adapt	No Adapt or Fertilize
Agriculture	−12.8	6.5	−16.9	12.5
Cooling	12.9	13.0	18.4	18.3
Deaths	2.3	2.4	13.1	13.1
All other	0.4	0.3	0.0	0.0
Total	2.8	22.2	14.7	44.0

of the benefit occurs in China. This is far in excess of China's share of world agricultural output. Recall that the pace of carbon fertilization is governed by a parameter that differs by region, k_r in Eq. (1). The value of k_r for China is higher than in any other regions except two areas with limited agricultural production. Thus FUND's estimates of carbon fertilization lead not only to a large aggregate impact, but to a striking concentration of that impact in China.

For adaptation, defined as the difference between the No Fertilize and the No Adapt or Fertilize scenarios, roughly half of the benefit of adaptation is a reduction in (the value of) climate-related deaths. Almost three-quarters (73.3%) of the global reduction in deaths occurs in sub-Saharan Africa. Adaptation occurs automatically in FUND, tied to per capita income; thus the model is telling an optimistic story about future economic growth in Africa and its ability to reduce climate impacts. Adaptation reduces the present value of climate-related deaths in sub-Saharan Africa to less than 20% of the no-adaptation value.

7. Conclusions

Models that are used to guide public policy play a dual role: they are simultaneously part of academic discourse and of political decision-making. The SCC estimated by averaging results from DICE, FUND and PAGE is a key component of U.S. climate policy, determining the value placed on the benefits of carbon reduction in government cost-benefit analyses.

FUND produces the lowest SCC estimates among the three models. We have examined aspects of FUND's damage estimates, finding three major factors that contribute to the low SCC values.

- Very large estimates of carbon fertilization, modeled as a positive effect on yields that is independent of other climate-related impacts, lead to projected benefits of carbon emissions that offset damages in other areas. Almost half of this benefit is projected to occur in China.
- Adaptation automatically caused by rising per capita incomes is assumed to reduce climate damages in many areas, notably including deaths due to climate-linked diseases such as malaria. Most of the automatic reduction in climate-caused deaths is projected to occur in sub-Saharan Africa.
- Finally, we noted but did not explore the near-absence of empirically significant damage estimates in 12 of FUND's 15 categories. This remains an important area for further research.

Our alternative scenarios are not intended as replacements for FUND's default assumptions. Rather, they are analytical constructs designed to demonstrate how much is at stake in fine-tuning these assumptions.

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