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## Human health and the social cost of carbon: a primer and call to action

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Over the past few decades we have improved our understanding of the health impacts of climate change.<sup>1</sup> While many public health researchers have contributed to this knowledge, relatively few are aware of how their work may relate to the Social Cost of Carbon (SCC). The SCC is a core economic concept in climate policy and one that can – and should – benefit directly from research produced by the public health community. The SCC’s importance was recently highlighted by this year’s Nobel Prize in Economic Sciences, which was awarded to William Nordhaus in part for his pioneering work developing models to estimate the SCC. Below we describe the SCC, explain how it is calculated, and provide some brief guidance on how health research can improve its estimation.

### **The Social Cost of Carbon**

The SCC is the net economic damage to society that results from one additional ton of CO<sub>2</sub> emissions. The SCC is widely used in regulatory cost-benefit analysis to value the impacts of CO<sub>2</sub> emissions, making it one of the most significant metrics in climate economics. In the United States for example, the use of the SCC in cost-benefit analysis is mandated by law, and it has been applied to dozens of federal regulations ranging from vehicle emission standards to power generation, including the Clean Power Plan.<sup>2</sup> Because the SCC represents the climate cost of releasing an additional ton of CO<sub>2</sub> emissions, from an economic perspective it also reflects the optimal carbon tax level to apply in a carbon tax regime, should governments choose to adopt one.

Called “the most important number you’ve never heard of”<sup>3</sup>, the SCC that is officially recognized by the United States government for regulatory analysis is calculated by equally

weighting the outputs of three integrated assessment models (described below). Other governments (e.g. United Kingdom) have also used one or more of these models for the same purpose, or have based their SCCs on the US estimates (e.g. Canada, Mexico).

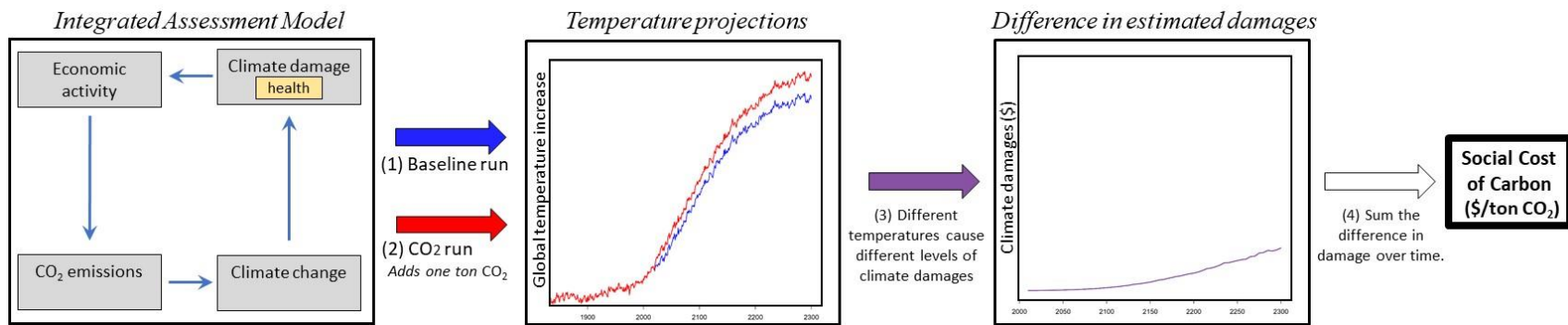
A distinguishing feature of these models is that their backbone is comprised of ‘damage functions’ - sets of equations that compute the harm to society that results from an extra ton of CO<sub>2</sub> emissions. These functions are based on empirical studies across multiple dimensions that estimate the potential impacts from climate change. These impacts are then monetized in an effort to place their relative harm to humans (economic and/or physical) onto a single scale.

Until now, most of the studies underlying damage functions have been undertaken by economists, including the studies quantifying health impacts; public health researchers have not been made active participants. In acknowledgement of this shortcoming (and others), a key recommendation of a recent National Academy of Sciences report was to improve damage functions by engaging all relevant experts and incorporating up-to-date disciplinary science.<sup>4</sup> Therefore, conducting research applicable to damage functions is a unique opportunity for epidemiologists and other health professionals to directly inform climate policy.

To that end, in the remaining sections we summarize the damage functions of the three leading models used to calculate the SCC, and argue that health experts should be fundamental to the process of updating these functions. We also briefly describe specific study design features that can help make research results applicable to future damage functions.

### **Damage functions in leading SCC models**

The three leading models used to estimate the SCC are the Dynamic Integrated Climate and Economy (DICE) model, the Policy Analysis of the Greenhouse Effect (PAGE) model, and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model. The former was developed in the USA and the latter two in Europe. These models each have an economic module and a climate module, which are linked (Figure 1). Changes in economic activity generate climate change by virtue of the emissions that are associated with that activity. At each time period, damages from climate change are monetized, aggregated, and then subtracted from GDP.



**Figure 1. Simplified schematic of how an integrated assessment model estimates the Social Cost of Carbon (SCC).** The left-hand box shows the basic features of the model and their linkages; namely, the economic component and climate component are linked through CO<sub>2</sub> emissions, which produce climate change and corresponding damages. To calculate the SCC in a given time period, one additional ton of CO<sub>2</sub> emissions is added to the model in that period. The cumulative discounted value of the resulting increase in future damages is the SCC at that time (relative to the baseline).

The three models differ in terms of which impacts are included in their damage functions and the degree of detail incorporated for each. Only FUND explicitly computes mortality and morbidity impacts, which are then transformed into economic damage. In contrast, the other two models (DICE and PAGE) do not directly estimate any specific type of impact but instead aggregate them in more generalized damage functions where a total amount of damage is computed, with human health implicitly assumed to comprise some percentage of that total. In this aggregated framework, the total damages are based on meta-analyses of individual studies which differ widely in terms of how health impacts are considered.<sup>5-8</sup>

Importantly, a number of climate-sensitive diseases that have become established in new locations – or are expected to in the future – are not currently featured (explicitly or implicitly) in existing damage functions. Examples include West Nile Virus, Lyme Disease, Zika Virus and Chikungunya.<sup>9-13</sup> Several other key health risks are also excluded (Table 1). However, even those health risks that are included are often based on incomplete or outdated estimates. For instance, one study used in DICE's damage function relies on the 1996 edition of the Global Burden of Disease, while cardiorespiratory impacts in FUND are based on mortality rates in 1990.<sup>14,15</sup> These shortcomings may partly explain why the health costs are small compared to those from many other sectors,<sup>8</sup> which does not correspond to more recent work.<sup>16,17</sup>

**Table 1. Examples of health risks included and excluded by the leading models currently used to calculate the SCC.** Note that there is some variability between models and that included risks may still be incomplete and/or based on outdated methods or data. See<sup>5,7,8,14,15,18,19</sup> for detailed documentation of what is included/excluded in the damage functions.

Examples of currently included health risks	Examples of currently excluded health risks
<ul style="list-style-type: none"> <li>• Dry-bulb<sup>1</sup> temperature exposure in adults</li> <li>• Vector-borne diseases (e.g. dengue, malaria)</li> <li>• Diarrhea</li> <li>• Mortality/morbidity from extreme weather events</li> </ul>	<ul style="list-style-type: none"> <li>• Wet-bulb<sup>1</sup> temperature exposure in adults</li> <li>• Temperature exposure (dry / wet bulb) in children</li> <li>• Malnutrition</li> <li>• Emerging infectious diseases (e.g. Zika)</li> <li>• Aeroallergen (e.g. pollen) impacts</li> <li>• Mental health impacts</li> <li>• Impacts of civil conflict</li> </ul>

<sup>1</sup> Dry-bulb temperature is the standard everyday measure of temperature whereas wet-bulb is a composite index that includes humidity. Wet bulb temperatures have been linked to adverse health outcomes, including infant mortality<sup>20,21</sup>.

An additional consideration is that some SCC models also estimate optimal decarbonization trajectories, derived by balancing mitigation costs against climate benefits. In the standard modeling framework, this tradeoff has ignored the potential near-term health impacts of mitigation – sometimes referred to as ‘co-benefits’ or ‘co-harms’. Recent studies<sup>22,23</sup> have demonstrated that, at least in the case of air pollution, these are likely to be net-positive overall despite opposing influences; the health co-benefits from improved air quality seem to outweigh the warming co-harms that may occur when reducing emissions of air pollutants such as SO<sub>2</sub> and NO<sub>x</sub> that act to cool the atmosphere. The implication is that SCC models may be recommending artificially low levels of mitigation if they omit health co-benefits. However, this result again depends in part on the damage functions calculating climate impacts; if warming is much more costly than currently assumed, the loss of the aerosol cooling effect could counterbalance more of the health benefit, a trade-off often neglected in the literature.<sup>24</sup>

### **Improving future damage functions**

The omission of numerous important health endpoints, together with the use of outdated data or methods to calibrate existing damage functions, underscores recent arguments that the human health impacts of climate change – and consequently the SCC – may be underestimated.<sup>17,25</sup> As a result, there is a clear need for health professionals to contribute to this research agenda if these damage functions are to be comprehensively upgraded.

Fortunately, compared to ten or twenty years ago when the studies underlying most of the current damage functions were conducted, our knowledge of climate-health relationship is substantially improved. This new knowledge is reflected in the publication of numerous recent



studies projecting the health impacts of climate change, several of which report large potential disease burdens.<sup>16,17,26-31</sup>

How would a large correction to these damage functions affect the SCC? As a single example, the authors of one recent econometric study calculated a partial SCC – estimated from mortality impacts alone – and found that it may be comparable to the full SCC employed under the Obama administration which included impacts across *all* dimensions, both health and otherwise.<sup>17</sup> Other studies are needed to confirm, expand, or revise this type of result and such research should be conducted in close collaboration with epidemiologists and other public health experts to ensure that the best possible science is applied.

New and improved damage functions that reflect our best scientific understanding require strong interdisciplinary collaboration as well as a clear procedure for non-economists to contribute to model development. Prototypes of modeling platforms that streamline this collaboration are underway (for example, see Resources for the Future’s Social Cost of Carbon initiative<sup>32</sup> and the Mimi modular modeling framework<sup>33</sup>). In addition, there are a number of features particular to the damage functions that health experts should consider when designing research studies related to climate change impacts (also see<sup>4,8</sup>). We highlight four:

- 1) Global and regional coverage: SCC models are global models comprised of individual regions, each with its own damage function. As a result, the ideal study to improve their estimation of climate impacts – for example from heat waves or extreme weather – would also be global in scope and would use uniform methods to assess all regions differentially. Although epidemiologists may not be entirely comfortable making inferences for areas with data limitations, excluding these areas would require other

(potentially non-specialist) researchers to extrapolate the results from one region to another.

- 2) Scenarios and metrics: Climate damage functions are generally continuous with temperature, though some impacts may additionally result from changes in sea-level rise, CO<sub>2</sub> concentrations, or ocean temperature. However, many health impact studies report results for only one or a few time-points or temperature/emission scenarios. These studies cannot be readily matched to SCC models. We recommend that researchers conduct their evaluations across as wide a range of scenarios and time horizons as possible. Additionally, because future paths are multi-dimensional (socioeconomic, climatic etc.),<sup>34</sup> framing results solely as the number of additional deaths or life years lost from climate change can sometimes be difficult to contextualize; multiplicative effect estimates (e.g. incidence rates; fraction of attributable deaths) are preferable.
- 3) Vulnerable groups: Experts generally agree that the poor and disadvantaged will suffer the most from climate change.<sup>35,36</sup> Therefore, it is important that human health research attempts to characterize climate risks in vulnerable populations. Groupings to consider include gender, age, urban/rural populations, income quantiles, and other populations of concern. Building such evidence will make it possible to take advantage of a powerful and unique feature of SCC models – their ability to analyze policy while explicitly accounting for societal preferences about fairness and equity.<sup>37,38</sup> Specifically, the models include a *social welfare function*, an equation which translates economic measures (dollars) into estimates of wellbeing, thus giving researchers and decision

makes the ability to compute the SCC with alternative choices about how much to prioritize specific populations. For example, previous work has shown that if climate change will in fact disproportionately harm the poor, then the SCC would be much higher – perhaps by an order of magnitude – than suggested by conventional estimates that ignore the distribution of burdens.<sup>38</sup>

- 4) Social change and adaptation: Over the coming decades, societies will experience rapid changes that may affect their vulnerability to climate impacts. Some types of change, such as demographic transitions, can affect climate vulnerability without adaptation, but the adoption of explicit adaptation measures is also likely. Many studies have already documented sizeable reductions in climate vulnerability over time, at least for certain health outcomes.<sup>39-41</sup> Nevertheless, these features are still routinely neglected in estimates of future health burdens, which limits their use in SCC models.

The above criteria refer specifically to the quantification of health outcomes, but a change in health status across a population also produces a cascade of economic consequences, which is ultimately how climate damage functions value climate impacts. For instance, increased mortality or morbidity can affect labor supply and productivity, population growth, overall economic productivity and so on.<sup>6,16,39,42,43</sup> A gold-standard study would include both the physical (e.g. deaths) and economic effects of climate-induced health burdens; the importance of these economic adjustments has been discussed elsewhere.<sup>4,8</sup>

### **An example from the literature**

For further illustration, we highlight some of these issues by way of a recent study by Gasparrini et al. (2017) that used a dataset of daily deaths from 451 locations in 23 countries to project future all-cause mortality from outdoor temperature. The authors first estimated location-specific exposure-response relationships, and then projected deaths under different climate change scenarios. Although this study uses state-of-the-art epidemiological methods, and is the largest of its kind, it does not meet all the criteria described above:

- Despite the expansive dataset, the majority of the world's countries and regions are excluded, including several populous regions that may be highly vulnerable to climate change (e.g. Africa, South Asia). Providing specific guidance on how to estimate temperature effects in data-sparse regions is beyond the scope of this paper, but promising avenues include advanced spatial smoothing techniques and extrapolation based on correlated indicator variables, such as macroeconomic measures or population characteristics. We also note that Demographic and Health Surveys are continually released and include ever more detail<sup>44</sup>; although not directly applicable to the study design of Gasparrini et al., DHS surveys allow for the estimation of temperature effects using other methods.<sup>20</sup>
- The study did analyze multiple climate scenarios and time periods that would thus enable the estimation of burdens across a continuous range of temperatures.
- The study does not consider subgroups and assumes no demographic changes. The latter has the advantage of isolating the impact of climate change, but disregards the influence of population growth and composition. These effects could be at least partially incorporated by applying age-sex stratified exposure-response relationships –

increasingly common in the literature<sup>45,46</sup> – to long-term mortality projections, which are available (by age and sex) from the United Nations as well as the Shared Socioeconomic Pathway project.<sup>47,48</sup>

- The study assumes no adaptation. As with extrapolation to data-sparse regions, future adaptation effects could potentially be explored using projections of macroeconomic or population variables.

Much of this discussion centers on dealing with data limitations, whether in geographic regions, sub-populations or about the future. We are aware of several ongoing projects aiming to apply epidemiologically-based approaches to these problems. Another method is to employ simple sensitivity tests that span the range of possibilities. This approach has been used with SCC models in the past, for example to bound the possible implications of alternative pathways of future economic development and to analyze within-country inequalities.<sup>38,49</sup>

## **Conclusion**

The SCC is one of the most influential metrics in climate policy. It depends critically on the potential human health impacts of climate change, but our best estimates of these impacts are not currently incorporated into the leading SCC models. Likely reasons include a lack of communication between disciplines and a lack of true interdisciplinary teams, as well as the time gap between the production of evidence and its use in policy applications. Therefore, as the SCC modeling community prepares to move towards a new generation of models, it is imperative that we avoid previous pitfalls by ensuring that the public health community

contribute its expertise, both through the inclusion of existing evidence and through the design of future studies.

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