Updating the United States Government's Social Cost of Carbon

Supplementary Materials

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S.I. Spatial Resolution of the Climate Module

In the main text, we recommend that the simple Earth system model Finite Amplitude Impulse Response (FAIR), which satisfies all climate model criteria set by the National Academies of Sciences, Engineering, and Medicine (NASEM), be used in an updated SCC to project changes in global mean surface temperature (GMST). A strength of simple climate models like FAIR is that they can project GMST, accounting for climatological uncertainty, both with and without a marginal increase in emissions, which is necessary to compute the social cost of one additional ton of CO_2. However, they are not able to provide local climate projections at, for example, the county level. This introduces a challenge, as socioeconomic trajectories are available nationally and, as discussed in Section IIA of the main text, recovering a valid damage function requires that climate impacts be estimated locally.

However, it is possible to use high spatial detail in socioeconomic and climatic conditions to estimate damages that are then calibrated to GMST (and GMSL, for sectors where sea level rise is an important driver of climate change impacts) in a second stage (NASEM, 2017; Carleton et al., 2021; Rode et al., 2021a,b). Therefore, we additionally recommend that the damage function itself relate total socioeconomic damages at global scale to changes in global mean surface temperature (and global mean sea level rise where appropriate).

S.II. Top-down GDP-based Estimates of Climate Damages

Another approach to updating damage functions guided by the three listed criteria in Section II.A of the main text is "top-down" in nature, relying on statistical relationships between GDP and climate variables (generally, temperature) to quantify the impacts of climate change on aggregate growth in (or levels of) income (e.g., Burke et al. 2015; Dell, Jones and Olken, 2012). The idea is to use GDP as a wide-reaching measure of economic well-being such that individual socioeconomic sectors do not need to be separately analyzed nor do their interactions need to be explicitly modeled. These top-down empirical results have recently been used to compute updated SCCs. For example, Ricke et al. (2018) use statistical estimates from Burke et al. (2015) and Dell et al. (2012) to generate SCCs on the order of about $400, nearly an order of magnitude larger than the Obama SCC.

This is an important and rapidly evolving line of research. However, several critiques cause us to conclude that top-down empirical analysis is not currently ready for use in determining the SCC. First, GDP is an incomplete measure of economic well-being and of willingness-to-pay for reducing greenhouse gas emissions. For example, it misses non-market outcomes such as mortality and morbidity that are large in magnitude (Hsiang et al., 2017), and current top-down analyses omit the damages associated with flooding and sea level rise. However, a bottom-up approach that sums sector-specific damages will also be incomplete, as discussed in this paper's last section.

Second, there is a long history of skepticism about the ability of cross-country GDP regressions to provide reliable information on the determinants of growth.[1] Many of these

[1] Note that this skepticism in the macroeconomics literature has applied both to purely cross-sectional analyses (comparing countries' growth experiences to one another) and to growth regressions exploiting panel data (comparing GDP over time within a country). See Durlauf (2009) for a detailed discussion.

concerns boil down to questions of misspecification. Regression models can be designed to identify causal relationships between various phenomena—in this case, between GDP growth and its potential causes. With limited available data, however, it is difficult to specify a regression model that can accurately recover the dynamic and potentially slow-moving influence of individual determinants of growth. Moreover, in GDP regressions, each country-year observation is treated as independent from the others, when in fact the growth process is strongly interlinked across countries (Klenow and Rodriguez-Clare, 2005). Modeling these interdependencies across space and time is exceptionally difficult with available data.

Third, it is unclear whether a change in temperature affects the level or growth rate of GDP. A test for growth effects of temperature shocks requires estimating a distributed lag model with many lags, but these models (which measure the effects of temperature on growth over time) are difficult to estimate with available data, leaving a good deal of uncertainty in the results. For example, Burke et al. (2015) are empirically unable to distinguish between growth and level effects,[2] while Kalkuhl and Wenz (2020) reject evidence of growth effects and Burke and Tanutama (2020) find evidence in support of growth effects (at the subnational level). The answer to this question has first order consequences on climate change projections, so this lack of clarity is not trivial.

Fourth, a paper in this literature notes that the estimated effects of temperature shocks on GDP growth rates appear implausibly large: "If an extra 1°C reduces growth by 1.1 percentage points, then it would take only eight years of sustained temperature differences to explain the overall cross-sectional relationship between temperature and income observed in the world

[2] Burke et al. (2015) estimate a 5-year distributed lag model that cannot reject zero growth effects (cumulative effect of -0.010 per °C with a 95 percent confidence interval of [-.027, 0.008]). The authors conclude: "...we cannot reject the hypothesis that this effect is a true growth effect[s] nor can we reject the hypothesis that it is a temporary level effect."

today" (Dell, Jones and Olken, 2009). The magnitude of these effects along with concerns about whether there are plausible mechanisms through which temperature can affect economic growth (as opposed to the level of economic activity) together have led to some additional skepticism.

A top-down approach to damage function estimation has strong potential to inform the SCC, particularly because it is challenging to empirically ground the overlap, spillovers, and interactions among individual sectors of damages used in a bottom-up approach (NASEM, 2017; Kopp and Mignone, 2012). Therefore, resolving the uncertainties in this expanding literature is an urgent line of inquiry. In the meantime, we believe that a bottom-up approach like that outlined in the main text is a more promising avenue for determining an SCC grounded in real-world data.

S.III. Challenges to Updating Existing IAMs

One possible SCC updating approach would be to closely mimic the original IWG structure. This requires updating each of the seven SCC ingredients *within* the three IAMs wherever possible. One would then run each of the updated versions of these three models and produce new distributions of SCCs. An appeal of this pathway is that it is relatively straightforward to replace the existing climate models in each IAM with the FAIR model, including the construction of a semi-empirical model of sea level rise. Moreover, this approach would allow the government to rely on the original IAM model parameters when updated scientific evidence is not available or cannot objectively inform a key modeling decision.[3]

The Achilles heel of this potential approach is that while the ultimate goal of the exercise is to estimate the damages from an additional ton of CO_2, there is not a compelling way to incorporate the latest evidence on climate change damages. The challenges are both conceptual and practical.

On the conceptual side, it is not straightforward to replace the existing IAM damage functions with improved damage functions. In the case of FUND, it is possible to subdivide the overall damage function into sector-specific functions that can roughly be mapped to the existing improved sectoral damage functions.[4] But the result would be an imperfect melding of new, scientifically robust analysis with older modeling assumptions that are only loosely tied to empirical evidence. The challenge of replacing the damage functions in DICE and PAGE is even

[3] For example, some sectors have insufficient empirical evidence for damage function calibration (e.g., ecosystem services). Similarly, evidence on the climatological likelihood and socioeconomic impact of tipping points such as ice sheet melt, breakdown of ocean currents, or release of methane from the permafrost are lacking.

[4] For example, energy demand in FUND can be mapped directly to the energy demand damage function derived in Rode et al. (2021a), while the mortality damage function empirically derived in Carleton et al. (2021) covers only some of the causes of death forming mortality-related damages in FUND.

greater, because their overall damage functions cannot readily be subdivided into categories that map to the empirically founded sectoral damage functions. The best case is that there would be some risk of double counting and then a mixing of the newer, empirically founded and the older, assumption-driven approaches with unclear weightings between the two. Overall, there is not a clear correspondence between empirically-founded, sector-specific damage functions and IAM damage functions, which makes combining them conceptually complicated.

On the practical side, the nature of recent damage function estimates makes it challenging to replace components of the existing IAMs' damage functions with these new, empirically-founded sectoral damage functions for at least two reasons.[5] First, none of the existing IAMs have sufficient spatial resolution in socioeconomic projections to align population and income trajectories with new damage functions that reflect differences in climate change impacts at the local level (e.g., county). Second, adaptation is treated differently in each model (Diaz and Moore, 2017; Moore et al., 2017), such that adjustments to incorporate real-world evidence on sector- and region-specific adaptation will require substantial changes to each model's original structure.

In addition to these challenges, it would be difficult to fully follow the recommendations above with respect to both the valuation of uncertainty (Ingredient Six) and the treatment of equity (Ingredient Seven). With respect to uncertainty, DICE is not designed to account for the many uncertain parameters in the SCC calculation, and FUND and PAGE can only enable valuation of uncertainty to the extent that sector-specific damage functions and their

[5] Initial efforts to update the damage module within a single IAM have each constituted significant academic publications, given the challenges involved in conforming new, generally richer, information to the existing IAM frameworks. For example, Moore et al. (2017) replace the agricultural damage function in FUND using a meta-analysis of the empirical agricultural impacts literature, and Bressler (2021) does the same by adding a mortality damage function on top of existing DICE damages.

corresponding uncertainties can be integrated into the modeling framework; as discussed above, this is not a straightforward task. If equity weighting were pursued, the low spatial resolution of all IAMs limits their ability to capture and value differences in the welfare effects of climate change.[6]

Therefore, while updating existing IAMs was recommended by the NASEM for use in the near-term, the integration of new, empirically founded sectoral damage functions into the existing IAMs has conceptual inconsistencies and is likely to be practically challenging. Thus, it cannot fully accommodate one of the key advances in understanding about climate change that have taken place in the last decade.

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[6] Note that one possible solution would be to incorporate equity weighting into the aggregate damage function of each IAM by valuing welfare differences across high-resolution empirical damage estimates. This is discussed in Supplementary Materials Section S.IV. However, this is only feasible within the IAMs to the extent that sector-specific damage functions can be integrated into each IAM; the challenges to doing so are discussed above.

S.IV. Building a New IAM Under an Updated Circular A-4

Section III of the main text details an implementation pathway for constructing a new SCC framework under the United States Government's current approach to cost-benefit analysis. However, if OMB Circular A-4 were updated to allow for more flexibility in the valuation of climate change damages, both endogenous discounting (Ingredient Three) and the valuation of equity (Ingredient Seven) would become practically feasible. If this were to take place, we recommend building a new IAM that follows the exact same SCC framework described in the main text, but replaces constant discounting and no equity weighting with a flexible valuation approach that includes Ramsey discounting, equity weighting, and multiple treatments of uncertainty valuation.

This approach is based on a single economic principle—declining marginal value of consumption—that underlies the motivation for discounting *as well as* the valuation of both equity and uncertainty (Anthoff et al., 2009). This principle derives from the straightforward observation that $100 is worth more to a poor person than a wealthy one. In the climate setting, declining marginal value implies that one should attach a higher value to future *and* present impacts of climate change when they occur to lower income populations. It also means that when future incomes are uncertain, one must account for the risk of severe damages occurring when incomes are low, and thus when the value of an additional dollar is relatively high (Jensen and Traeger, 2014).

A holistic approach that would incorporate the implications of declining marginal value of consumption throughout the entire valuation of climate damages would be possible analytically with a new, empirically founded IAM. This could be done by computing an SCC in which the damage function represents the difference in the "certainty-equivalent" value of consumption across all years, populations, and possible future states of the world with and without climate change.[7] In this approach, damage valuation is conducted from the perspective of a person who does not know their circumstances in advance, so they account for all potential income levels (e.g., whether they earn $25,000 or $250,000 annually) and degrees of climate risk they might face (e.g., whether they live in Miami or Minneapolis or outside the United States).

Under this approach, discounting, uncertainty valuation, and equity implications are all incorporated into a single, certainty-equivalent damage function.[8] To compute this damage function, estimates of local-level climate change damages and their associated probabilities are combined with evidence on how the marginal value of consumption declines as people become wealthier. This calculation is possible only with updated damage estimates from the recent literature that fully capture socioeconomic, statistical, and climatological uncertainty at a local level. This pathway is under development at the Climate Impact Lab and will be released in Fall 2021 (Nath et al., 2021).

This approach reflects an intellectually coherent approach for a *global* social planner to value damages from climate change, but it is not without its challenges. First, it depends on the specification of a particular utility function. Under a standard constant relative risk aversion utility function, a single utility function parameter, η, is needed for the calculation. In contrast, alternative utility formulations, such as Epstein-Zin utility, allow for separate parameterizations for the degree of risk aversion and degree of inequality aversion (Cai and Lontzek, 2019). The choice of utility function and its parameterization can have substantial impact on the resulting SCC (Cai and Lontzek, 2019; Lemoine, 2021). Therefore, if pursued, this approach should

[7] This approach is similar in spirit to John Rawls' "veil of ignorance" thought experiment, in which an individual makes decisions about social policy without knowing who in that society they will be (Rawls, 1971).
[8] A similar certainty-equivalent welfare metric was derived in Jones and Klenow (2016) to compare historical well-being across countries.

include multiple alternative utility formulations, including those which allow for the separate treatment of discounting, equity, and uncertainty so that policymakers can flexibly choose between multiple economically justified valuation options.

Second, choices about the utility function imply judgments about where marginal changes in consumption are more valuable, both within the United States and across countries. While a global certainty-equivalent damage function as described above is reasonable for a global social planner, whether it is appropriate for a particular country (e.g., the United States Government) or jurisdiction is ultimately a political judgment. Relatedly, the United States Government's approach to cost-benefit analysis currently treats monetary losses (and gains) the same, regardless of who is affected, so that a loss/gain that accrues to a poor person is valued the same as one that accrues to a rich one. Thus, the adoption of this approach would require a fundamental change in cost-benefit analysis that would likely have precedential implications for other domains and this would presumably require updates to Circular A-4.

S.V. Points of Departure from the National Academies of Sciences, Engineering, and Medicine

In 2017, the National Academies of Sciences, Engineering, and Medicine (NASEM) published a comprehensive report detailing recommendations for updating the SCC (NASEM, 2017). For the most part, the recommendations we outline in the main text reflect conclusions reached in the NASEM report. However, drawing on updated evidence since the report was published, we depart from NASEM guidance in three key areas, which we detail here.

First, we recommend that the Shared Socioeconomic Pathways (SSPs) be considered a valid source of projected socioeconomics, even though NASEM rightly points out that the SSPs are limited in their temporal scope and their ability to characterize uncertainty (NASEM, 2017; p. 66). Unfortunately, NASEM's proposed solution, which combines expert elicitation with probabilistic projections and regional and sectoral downscaling, has yet to be established in the scientific literature. Rennert et al. (2021) have made an important contribution to this literature, constructing probabilistic projections of population, income, and emissions that carefully meet all NASEM projection criteria. However, these projections are not yet peer-reviewed nor publicly available. Therefore, while we agree with NASEM that much more can be done to improve emissions and socioeconomic projections for use in SCC calculations, we recommend SSPs, and their temporal extrapolation and combination with the RCPs (e.g., Rode et al., 2021a), be considered as the best currently available approach to projection of socioeconomics and emissions.

Second, we recommend that under current OMB Circular A-4, a constant discount rate should be used, although its level should be lowered to reflect recent changes in global capital markets. In contrast, NASEM recommends Ramsey-based prescriptive discounting approaches that endogenize the discount rate to future economic growth (and its uncertainty). However, we also argue that if Circular A-4 were updated to allow more flexibility in discounting approaches, many different valuation possibilities would arise, including the application of Ramsey-like discounting. We discuss these possibilities in Section III of the main text and above in Supplementary Materials S.IV. However, we believe that current Circular A-4 makes the Ramsey-based approach pragmatically infeasible in the near-term, and we underscore that applying the Ramsey equation requires several judgements about the values of key parameters.

Finally, we emphasize the economic rationale for and empirical feasibility of including the valuation of uncertainty and equity in updated SCC calculations (Ingredients Six and Seven), while NASEM leaves these two issues largely unaddressed. This departure likely arises because of newly available probabilistic climate change damage estimates at high spatial resolution (e.g., Rode et al. 2021a), which were not available four years ago and make the full accounting for uncertainty and equity now feasible. Again, we underscore that we think that the valuation of uncertainty is much more straightforward to implement currently, than is the case with equity.

Supplementary Figures

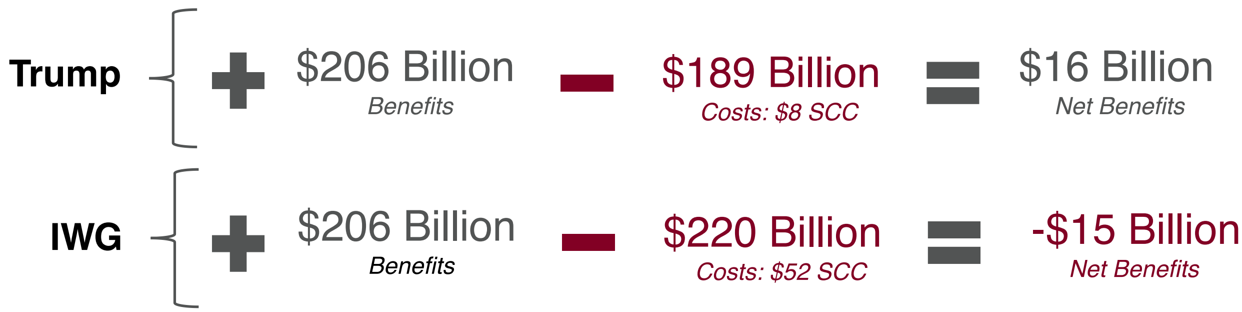

Figure S1: Trump Administration SCC used to justify rollbacks of fuel-economy standards. Figure displays an example regulatory cost-benefit analysis (CBA) using two different SCCs. The values shown are the costs and benefits of a 2017 Environmental Protection Agency (EPA) and National Highway Traffic and Safety Administration (NHTSA) rollback of fuel economy standards for 2021-2026 model-year vehicles. The top row displays benefits and costs of the rollback using the 2017 Trump Administration 3 percent discount rate SCC (EPA and NHTSA, 2018), taken from Table I-I and Table VII-286 of EPA and NHTSA (2020). The bottom row uses the same benefit estimate, but values the costs using the 2016 IWG 3 percent discount rate SCC (i.e., the Biden Administration "interim" SCC), leaving all other assumptions the same across rows (IWG, 2016). We assume a constant ratio between the Trump and IWG SCCs, leading to a conservative estimate of the IWG SCC costs, since this ratio actually grows over time (although data on its evolution are unavailable). Cost estimates incorporate damages from carbon emissions and other factors, such as the monetary cost of fuel, with non-carbon costs accounting for $184 billion in both rows. Values are converted to 2020 USD using the annual GDP Implicit Price Deflator values in the U.S. Bureau of Economic Analysis' (BEA) National Income and Product Accounts Table 1.1.9.

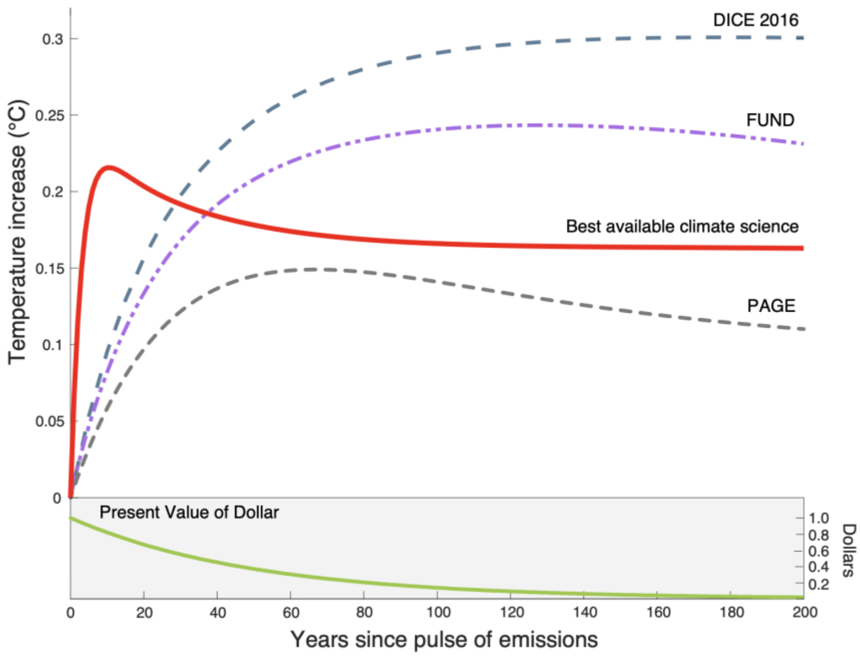

Figure S2: Current Integrated Assessment Models do not reflect well-developed climate science. Dynamic temperature response to a 100GtC impulse of CO_2 from the CMIP5 climate model ensemble (red solid line, labeled "best available climate science") versus the three IAMs used to compute the U.S. government's SCC (DICE, FUND, and PAGE). The lower panel shows the present discounted value of $1, discounted using a 2 percent discount rate. Source for top panel: Dietz et al., 2020.

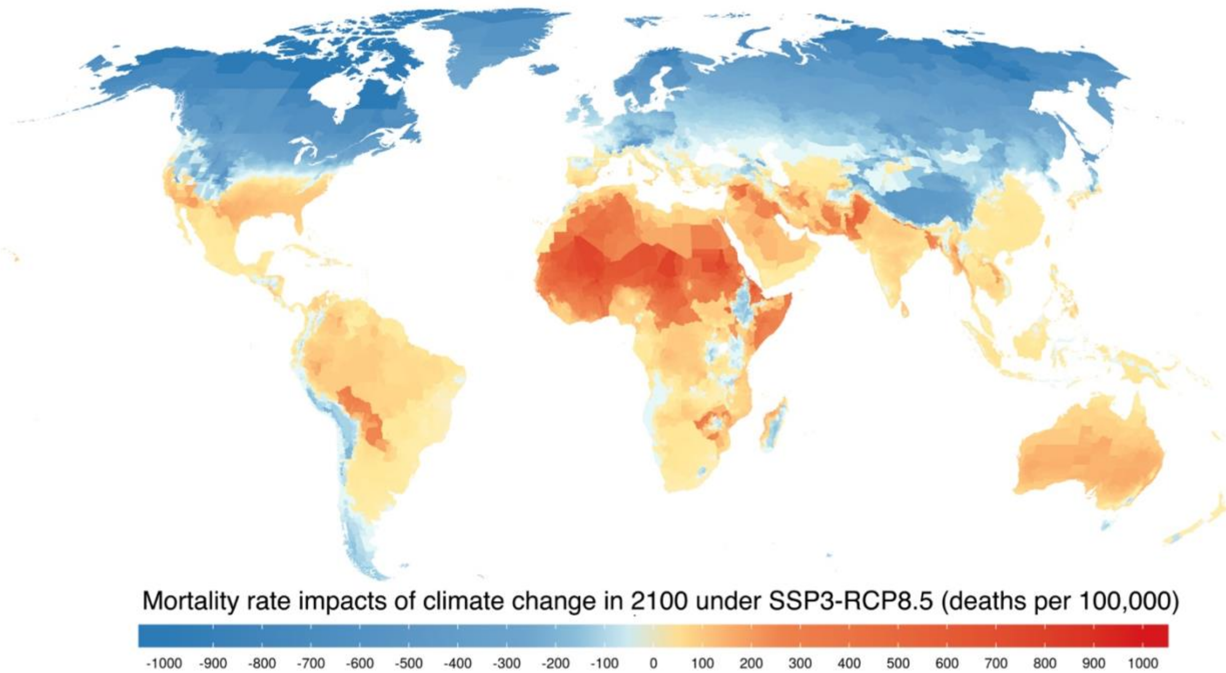

Figure S3: The mortality impacts of future climate change. The map indicates the impact of climate change on mortality rates, measured in units of deaths per 100,000 population, in the year 2100. Estimates come from a model accounting for the benefits of adaptation and income growth, and the map shows the climate model weighted mean estimate across Monte Carlo simulations conducted on 33 climate models and resampling from econometric uncertainty. Values shown refer to the RCP8.5 emissions scenario and the SSP3 socioeconomic scenario. *Source:* Carleton et al. (2021).

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