Intragenerational Equity in the Social Cost of Carbon*

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The social cost of carbon (SCC) reflects a partial estimate of the monetary damages caused by an incremental metric ton of CO_2 emissions. The Environmental Protection Agency (EPA) recently released a long-awaited update to the SCC, increasing its preferred value from \$51 per tCO_2 to \$190 per tCO_2. This is the first time the mortality impacts of climate change have been included in the SCC, reviving contentious debates about whether to monetize mortality risk with a value of a statistical life (VSL) that varies with income or remains constant across the population. The EPA diverges from past practice and uses an income-elastic VSL in its updated SCC, therefore assigning greater value to statistical lives in high-income countries than low-income countries. This senior essay proposes two alternative approaches, both of which assign equal value to all statistical lives: (1) using a global average VSL as an extension of past practice and (2) equity weighting—assigning greater weight to dollars in lower-income individuals' hands. I ultimately defend the use of a global average VSL on ethical, economic, and practical grounds. I then implement each approach in the new open-source Greenhouse Gas Impact Value Estimator (GIVE) model, one of three models used by the EPA in its updated estimate. My preferred mean SCC is \$380 per tCO_2 (\$10-\$998 per tCO_2: 5%-95% range, 2020 US dollars), double the EPA's proposed value. If used in benefit-cost analysis, this SCC would substantially increase the estimated benefits of climate change mitigation by reflecting that the harms of climate change are not borne equally across society.

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1 Introduction

The social cost of carbon (SCC) is the central tool used in executive branch climate change rulemaking. A given policy will pass benefit-cost analysis if the climate benefits exceed the economic cost of the associated emissions reductions. Climate benefits are calculated by multiplying the change in CO_2 emissions caused by the policy by the SCC. For this reason, some refer to it as the single most important economic concept in the economics of climate change (Nordhaus, 2017).

The US government has used the SCC in benefit-cost analysis of regulations with more than $1 trillion of benefits, including the standards for appliance energy efficiency and vehicle and power plant emissions (Rennert et al., 2022; Nordhaus, 2017). It is the basis for proposed federal carbon prices, state-level carbon prices, federal and state-level tax credits, analogous metrics in Canada and Israel,[1] and a variety of corporate and institutional policies (Rennert et al., 2022).[2]

In November 2022, the Environmental Protection Agency (EPA) increased the SCC from $51 per tCO_2 to $190 per tCO_2 (all SCC values are in per tCO_2 units hereafter).[3] The updated value reflects a novel and improved methodology: a new climate model, better socioeconomic projections, and separate estimates of damages from several sources, including temperature-related mortality (NASEM, 2017). This is the first time the mortality impacts of climate change have been explicitly estimated and valued in the US government's SCC.

However, the EPA makes a quiet but exceedingly important methodological choice in

[1]Many countries and international institutions have either already explicitly adapted the US estimates of global damages in their domestic analyses (e.g., Canada and Israel), developed their own estimates of global damages (e.g., Germany), or taken note of the US estimates in their assessments of climate policies (e.g., India's National Green Tribunal, the Australian Capital Territory, New Zealand, and the International Monetary Fund)

[2]At least 14 state governments used the SCC to guide policy (Institute for Policy Integrity, 2022). For example, Illinois and New York used the SCC to value "zero-emissions credits" paid to clean energy producers (Carleton and Greenstone, 2022).

[3]The last full update to the SCC was done by the Interagency Working Group (IWG) in the Obama Administration in 2016 (IWG, 2016). The SCC was decreased to $1 per tCO_2-$8 under the Trump Administration (The White House, 2017). The Biden Administration released an interim estimate of the SCC as $51 in February 2021, matching the Obama-era value adjusted for inflation (IWG, 2021).

the calculation of mortality damages: they use a benefits-transfer approach to monetize the benefits of avoided mortality risk, which means that statistical lives are assigned a higher value in high-income countries than in low-income countries. The stakes of this decision are exceedingly high. Given that temperature-related mortality impacts are the largest source of damages in the updated SCC, the decision to approve or reject a proposed regulation turns on the selected method for valuing premature deaths (Rennert et al., 2022; Carleton et al., 2022). Further, the updated SCC is the first benefit-cost calculation that explicitly projects and monetizes premature mortality in other countries caused by US policy decisions.[4] The monetization of excess deaths in the context of the SCC will be precedent-setting for future analysis of global externalities. Finally, a monetization approach lacking precedent could be the focus of future challenges to the SCC in court.

Despite the importance of this issue, the consequences of distinct approaches to monetizing the mortality damages from climate change are not well documented or understood. This senior essay provides new evidence on the impact of three approaches to monetizing premature mortality in the estimation of the SCC using the Greenhouse Gas Impact Value Estimator (GIVE) model.

The first approach, and that which the EPA uses to justify their methodology in the updated SCC, is the Kaldor-Hicks potential compensation criterion. I refer to this is approach as "pure Kaldor-Hicks" for conceptual clarity. The Kaldor-Hicks criterion states that there is an increase in social welfare if those who benefit from a given policy could fully compensate those who are harmed from the policy and still remain better off. In order to evaluate if potential compensation is possible, one needs an estimate of an individuals' willingness to pay. This is straightforward for market goods. However, for non-market goods such as premature mortality risk, agencies must use alternative means to estimate willingness to pay.

[4] To the best of my knowledge, there is no precedent for a Regulatory Impact Statement (RIA) explicitly projecting and monetizing premature deaths caused in other countries by US policy decisions (Bressler and Heal, 2022). A few RIAs have considered impacts in other countries but have not monetized them. For example, the Mercury and Air Toxic Standard discussed the foreign health benefits of US mercury reductions, but did not quantify them (EPA, 2011). A NASA report considered mortality impacts from falling debris in the US and other countries but did not monetize the impact (NASA, 1996).

For premature mortality risk, agencies use the value of a statistical life (VSL).[5] Since VSL estimates are not widely available for other countries, EPA extrapolates the willingness to pay of those outside the US as a function of per capita income, which is what leads to a higher value placed on premature mortality for higher income regions. A common approach in academic literature is also to use an income-elastic VSL; however, most studies do not typically invoke the Kaldor-Hicks criterion as a justification—they simply take revealed preference as a first principle.[6]

The second approach, and that currently practiced by the US in all domestic benefit-cost analysis, is identical to the Kaldor-Hicks approach with one major exception: it accords equal dollar value to all statistical lives regardless of income. This is the "domestic status quo" approach. Although economic theory assumes a low-income individual will have a lower willingness to pay to avoid mortality risks than a high-income individual, federal agencies have long used a single population VSL in regulatory review. A rule that passes the Kaldor-Hicks potential compensation criterion may not pass US benefit-cost analysis, and vice versa. Therefore, while the Kaldor-Hicks criterion serves as the "underpinning" of the federal agencies' domestic benefit-cost analysis, agencies do not follow it when calculating the benefits of avoided mortality risk because of "difficult moral, ethical, and political issues" (EPA, 2000). Note that status quo is a misnomer here given the EPA itself did not follow status quo benefit cost analysis in the most recent update to the SCC. An approach consistent with previous practice would have used a global average VSL to estimate the SCC—just as the EPA uses a US average VSL in domestic benefit-cost analysis.

The final approach—"equity weighting"—offers an appealing alternative to the ethical concerns introduced by the pure Kaldor-Hicks approach and the theoretical inconsistencies

[5] There is a large and contentious literature on both the estimation of VSL and its use in government. VSL is estimated in labor markets where there are tradeoffs between small amounts of additional near-term safety and higher wages. It is not intended to represent the government's assessment of the "value of a life", but rather individuals' trade-offs of higher wages for mortality risk reductions.

[6] The default version of the damage functions used to calculate the updated SCC use an income-elastic VSL without any reference to the Kaldor-Hicks criterion (Carleton et al., 2022; Rennert et al., 2022; Diaz, 2016). Note also that revealed preference need not be income-based, though that is the most common approach.

in status quo approach. The equity weighting approach begins the same way as the pure Kaldor-Hicks approach by estimating willingness to pay in market dollars, but then applies weights to account for diminishing marginal utility of consumption. In other words, the Kaldor-Hicks approach accounts for individuals' trade-offs in terms of dollars-per-reduced-risk and then equity weighting adjusts those dollars to reflect that the same absolute consumption change results in a smaller welfare change for a high-income individual than a low-income individual. In this way, equity weighting maximizes a social welfare function that captures what a social planner would naturally care about: the ability of money to buy real net benefits and the welfare people get from those benefits (Bressler and Heal, 2022).

There is a long-standing literature that accounts for diminishing marginal utility in benefit-cost analysis. The literature is rooted in discussions of distributional weighting in the benefit-cost analysis literature (Mirrlees, 1978), but is known as equity weighting in the climate economics literature (Azar and Sterner, 1996; Fankhauser et al., 1997; Anthoff et al., 2009; Anthoff and Tol, 2010; Dennig et al., 2015; Anthoff and Emmerling, 2019). Equity weighted SCC estimates have been produced in three well-known integrated assessment models (IAMs): RICE (Nordhaus, 2011), FUND (Anthoff et al., 2009), and PAGE (Hope, 2008). The World Bank, the UK, and Germany have used an equity weighted SCC over the course of the past 20 years (Watkiss and Hope, 2011; Matthey and Bünger, 2019). That said, neither of the two models used by the EPA that disaggregate the spatial impact of damages use equity weighting (Rennert et al., 2022; Carleton et al., 2022).[7]

The first contribution of this senior essay is to bring together this climate economics literature on equity weighting and recent advances in calculating the SCC with the legal benefit-cost analysis literature—and then place them in the present context of the Biden Administration's proposed changes to regulatory review. In the past, agencies were directed not to consider the income-distributive consequences of regulations and instead provide a

[7]The third model used by the EPA is Howard and Sterner (2017), which is a single global region model. Equity weighting is therefore impossible.

separate description of distributional effects (OMB, 2003).[8] However, on his first day in office, President Biden instructed the Office of Management and Budget (OMB) to propose procedures for directly incorporating distributive considerations into agencies' benefit-cost analyses (The White House, 2021). On April 6, 2023—just over a week before the submission of this senior essay—OMB released draft revisions to its guidance on benefit-cost analysis encouraging agencies to account for the distributive consequences of regulations and outlining concrete methodology for constructing equity weights (OMB, 2023c,a). In this section of the paper, I aim to clarify the theoretical, ethical, political, and legal trade-offs between each approach in the context of the updated SCC. Equity weighting is the first-best approach from a theoretical perspective but may face legal challenge. I ultimately defend an extension of the status quo approach because it is most consistent with the logic behind the federal government's previous practice.

My second contribution is to translate each of the three approaches to benefit-cost analysis—Kaldor-Hicks, domestic status quo, and equity weighted—into the theoretical model for the calculation of the SCC. I show how an output-based model such as the standard version of GIVE is equivalent to a discounted utilitarian social welfare function with consumption elasticity of marginal utility (η) equal to zero. Following Bressler and Heal (2022), I prove that the mortality portion of the status quo SCC is equivalent to the mortality portion of the equity weighted SCC, while the non-mortality portion of the status quo SCC is equivalent to the non-mortality portion of the Kaldor-Hicks SCC.

Finally, my third contribution is to implement each approach in the GIVE model, one of three models used by the EPA in its updated estimate. I chose the GIVE model based on its state-of-the-art ability to calculate the SCC, its implementation of recent advances in probabilistic socioeconomics to account for uncertainty, and its open-source availability.[9] I

[8]However, recent studies of agencies' regulatory impact analyses have found that most contain little analysis of regulations' effects on particular groups (Robinson et al., 2016; Revesz and Yi, 2021).

[9]The model is built on the Mimi.jl platform, an open-source package for constructing modular integrated assessment models.

introduce an alternative component for calculating the damages from premature mortality based on Bressler et al. (2021), making this the first paper to make use of GIVE's modular flexibility and open source status. I am also among the first to analyze equity weighting in the GIVE model.[10] For each specification, I use a Monte Carlo approach that samples interrelated socioeconomic, climate, and damage function uncertainties to provide mean and median estimates of SCC values across 10,000 model runs.

I reach three main empirical conclusions. First, using a global average VSL or equity weighting substantially increases the SCC relative to using a country-level VSL. This result is driven by the distribution of mortality damages. Using a global average VSL or equity weighting increases the value of avoided mortality risk for individuals in low-income countries. My substitution of a more accurate damage function increases estimated damages in these countries, therefore increasing the SCC. Second, equity weighted estimates increase with inequality aversion, despite greater rates of inequality aversion yielding greater discount rates. This is because spatial inequality aversion outweighs the impact of discounting the future at a higher rate. Third, equity weighted estimates vary with the region to which weights are normalized. Normalization based on US income yields an SCC nearly five times higher than normalization based on global average income.

The rest of this paper is organized as follows. Section 2 provides a brief discussion of the philosophical and welfare economic concepts that provide the foundation for benefit-cost analysis as applied to climate change. Section 3 details the trade-offs between the three approaches to benefit-cost analysis as applied to the context of climate change. Section 4 presents the theoretical model for calculating the SCC under each of the three approaches. Section 5 describes the numerical model, Section 6 presents results, and Section 7 concludes.

[10] My approach is consistent with that used by a research group at UC Berkeley, whose work on equity weighting is forthcoming.

2 Foundations of welfare economics

Contemporary welfare economics is split into two branches (Fleurbaey and Maniquet, 2008). The first branch accepts interpersonal utility comparisons and uses social welfare functions to determine socially optimal outcomes. Section 2.1 describes this branch, which provides the foundation of climate economic models.[11] The second branch dismisses interpersonal utility comparisons and relies on the Pareto and Kaldor-Hicks criteria. Section 2.2 discusses this branch, which underlies governments' approaches to benefit-cost analysis around the world (Fleurbaey and Maniquet, 2011). These two branches are often implicitly combined in the application of climate economic models to benefit-cost analysis without direct reference to one another.[12] It is therefore useful to consider the development of these distinct branches to understand the the current paradigm.

2.1 The social welfare function

The concept of the social welfare functions originates with Ambram Bergson and Paul Samuelson (Bergson, 1938, 1954, 1948; Samuelson, 1947), and later by Amartya Sen in response to Arrow's impossibility theorem (Sen, 1970). The social welfare function framework presupposes consequentialism and welfarism (Adler, 2013). Consequentialism holds that a decision-maker faced with a choice between options should make her selection in light of the goodness ranking of the outcomes. Welfarism holds that the ethical goodness ranking of outcomes is reducible to the well-being, or utility, of individual people.

The social welfare function framework enables the comparison of the ethical goodness of two outcomes via a rule E for comparing their corresponding well-being vectors (i.e., the list of outcomes). Following Adler (2013), let $w_i(x)$ $\forall i \in N$ denote the numerical well-being indicator of individual i in outcome x, $w_i(y)$ the well-being number of individual i and

[11] For a more comprehensive discussion of the social welfare function approach, see Fleurbaey and Maniquet (2011).

[12] All integrated assessment models start with an explicit or implicit social welfare function, but are applied by governments in benefit-cost analysis without reference to the social welfare function (EPA, 2022).

outcome y, and so on. The most broad conception of the Bergson-Samuelson social welfare approach says that an outcome x is at least as good as an outcome y if $(w_1(x), ..., w_N(x))$ is ranked by E at least as good as $(w_1(y), ..., w_N(y))$.

Certain axioms determine the appropriate form of the rule E (Adler, 2013). The three most plausible axioms are ordering, anonymity, and Pareto: ordering is defined as the completeness and transitivity of the ranking of outcomes; anonymity is defined as each individual's interests receiving equal weight; and Pareto is defined as preferring x to y given everyone is at least as well off and at least one person is better off in x. Two further axioms are compelling on pragmatic grounds. Separability is defined as the independence of individuals whose well-being vectors have not changed. Finally, continuity means that if a well-being vector z is sufficiently close to x, and the well-being vector for x is ranked better than the well-being vector for y, then the well-being vector for z is also ranked better than the well-being vector for y.

Together, these axioms essentially eliminate all social welfare functions besides the utilitarian and prioritarian families of social welfare functions. Relaxing certain axioms or adding additional ones gives rise to new families of social welfare functions. The following sections discuss discounted utilitarianism—the dominant social welfare function used in the climate economics literature—before presenting alternative social welfare functions that account for critiques of discounted utilitarianism.[13]

2.1.1 Discounted utilitarianism

The standard social welfare function used in the climate economics literature is discounted utilitarianism. The discounted utilitarian approach uses a particular Bergson-Samuelson social welfare function that adds utility over all individuals and time periods:

$$W = \sum_{i=1}^{N} \sum_{t=1}^{T} U(c_{it}) r_t \tag{1}$$

[13] I am grateful to Simon Lang for an excellent literature review on this topic.

where W is the aggregated social welfare, $U(c_{it})$ is the utility of an initial i in period t and r_t is some discount factor at time t. The utility of individuals in future time periods is discounted to its present value to determine its contribution to social welfare. The objective of climate policy is to identify the path of emissions that maximizes social welfare.

2.1.2 Critiques of discounted utilitarianism and alternative approaches

While discounted utilitarianism is most commonly used in welfare-maximizing IAMs, it has been criticized on two accounts. Most notably, discounted utilitarianism is criticized for including an arbitrary time preference (in the case of a positive pure rate of time preference), which places a greater weight on present generations than on future generations (Adler, 2017; Roemer, 2011). Several prominent economists have argued that the pure rate of time preference should be zero or near-zero, which implies ethical impartiality among generations (Stern, 2006).[14] Weighting the utility of all individuals equally irrespective of the time they live in is known as classical utilitarianism.

Despite the appeal of impartiality among generations from an ethical perspective, the majority of economists do not subscribe to classical utilitarianism for a variety of reasons, including the claim that classical utilitarianism gives too little weight to current generations. Valuing all generations equally means that imposing an excessive sacrifice on the current generation may be welfare-increase given sufficient increase in the utility of future generations. Even a small increase in future generations' utility may outweigh large sacrifices to the current generation if there are a large number of future generations (Hepburn and Gosnell, 2014).

The second main criticism of discounted utilitarianism is that it is insensitive to the distribution of utility. Several alternative ethical theories address this claim. The maximin approach has the objective to maximize the well-being of the least well off (Rawls, 1971). Roemer (2011) advocates for the use of the maximin social welfare function in the intertemporal context of climate change, calling this approach "sustainabilitarianism." Maximin in the

[14] Stern (2006) argued that pure rate of time preference should near-zero in order to represent the probability that the world is going to end.

intertemporal context suggests that no generation should be better off than any other generation unless the increase in utility of a given generation can be achieved without reducing the utility of the worst-off generation (Roemer, 2011). The prioritarian approach is similar to the maximim approach in that it gives great weight, or "priority," to the least well-off rather that total weight to the least well-off. In practice, the prioritarian approach transforms personal utility to a social value using a strictly increasing and concave function (Adler, 2017):

$$W = \begin{cases} \sum_{i=1}^{N} \sum_{t=1}^{T} \ln\left(U(c_{it}) - U(c_{zero})\right) \; r_t & \text{if } \gamma = 1 \\ \frac{1}{1-\gamma} \sum_{i=1}^{N} \sum_{t=1}^{T} \left((U(c_{it}) - U(c_{zero}) \; r_t\right)^{1-\gamma} & \text{if } \gamma \neq 1, \end{cases} \tag{2}$$

where γ captures the degree of priority for the worse off, with larger values of γ indicating a greater degree of priority for worse-off individuals. The re-scaling $U(c_{it}) - U(c_{zero})$ ensures that individual utility is non-negative when c_{zero} reflects the required consumption level to attain a utility value of zero after rescaling.

Two final theories address both lines of critique. The Chichilnisky criterion requires that neither the present nor the future dictate outcomes (Chichilnisky, 1996). It maximizes a weighted average of the sum of a stream of discounted utilities plus the utility value of the last period (assuming a finite time horizon). Formally, the Chichilnisky criterion can be written as:

$$W = \alpha \sum_{t=1}^{\infty} U(c_t) r_t + (1-\alpha) \lim_{t \to \infty} U(c_t) \tag{3}$$

where α is a weight such that $0 < \alpha < 1$. The appropriate value for α is unresolved though some argue it should be very small in order to give a large weight to the utility of future generations.

Finally, the Mixed Bentham-Rawls criterion is similar in structure to the Chichilnisky criterion, but replaces the second term with the maximin criterion (Alvarez-Cuadrado and Van Long, 2009). The resulting social welfare function maximizes the weighted average of the sum of a stream of discounted utilities (the "Bentham term") plus the utility level of the worst-off generation (the "Rawls term").

2.2 New welfare economics and the origins of benefit-cost analysis

Classical economists were in broad agreement about the legitimacy of interpersonal comparisons of utility in the social welfare function approach. However, the development of positive economics in the early twentieth century and the appeal to make economics more "scientific" caused some to assert comparisons of utility illegitimate because of the inability to measure utility on a consistent scale (Robbins, 1935). This led to the development of what came to be known as "new welfare economics."

Under this framework economists start with the Pareto criterion, which maintains that there is an increase in social welfare if a policy does not harm any individual and makes at least one individual better off. However, the problem with the Pareto criterion is that it restricts the policies which economists can evaluate since most decisions involve trade-offs between making someone better and others worse off. Kaldor (1939) and Hicks (1939) separately proposed compensation criteria that could be applied more broadly. Kaldor's criterion states that a reallocation of resources is beneficial if the "winners" from this reallocation can fully compensate the losers and still be better off. Hicks' criterion is similar but is based on the bribery by losers rather than compensation by the winners. The criteria as first proposed individually, however, were theoretically inconsistent (de Scitovszky, 1941). To resolve this problem, de Scitovszky (1941) proposed that both the Kaldor and Hicks criteria had to be satisfied in order to attain a potential Pareto improvement. This is known as the Scitovsky double criterion, or more commonly, the Kaldor-Hicks criterion. Today, many economists advocate for something similar to a Bergson-Samuelson social welfare function to avoid the problems raised by this approach, yet it remains ubiquitous as the underpinning of government benefit-cost analysis (Fleurbaey and Maniquet, 2011).

3 Institutional background on benefit-cost analysis

This section evaluates three potential approaches to benefit-cost analysis. Section 3.1 provides a descriptive account of each approach, Section 3.2 provides a normative account, and Section 3.3 places the normative analysis in the context of the EPA's update to the SCC.

3.1 Three approaches to valuing avoided mortality risk in benefit-cost analysis

The approaches to benefit-cost analysis examined in this senior essay vary along two dimensions (Hemel, 2022). First, should premature mortality be valued at a population-wide value (equal-dollar VSL) or should it vary with individuals' estimated willingness to pay to avoid mortality risk (income-elastic VSL)? Second, should benefit-cost analysis continue to be distribution neutral or should it use equity weights? Under traditional distribution neutral benefit-cost analysis, everyone's dollars count the same. Under equity weighted benefit-cost analysis, low-income individuals' dollars account for the diminishing marginal utility of consumption. Table 1 shows how the three approaches to benefit-cost analysis vary along these two dimensions. Sections 3.1.1-3.1.3 describe each approach and how they apply to the estimation of the SCC.

Table 1: Three approaches to BCA

	Income-Elastic VSL	**Equal-Dollar VSL**
Distribution Neutral	Pure Kaldor-Hicks	Domestic Status Quo
Equity Weighted	Equity Weighted	-

Notes: Table based on Hemel (2022). The lower right corner of this matrix—equity weighted benefit-cost analysis with equal-dollar VSLs—is discussed in Hemel (2022), but this paper leaves it out for the sake of clarity given it is purely hypothetical and not suitable for use in the regulatory context.

3.1.1 Pure Kaldor-Hicks

The pure Kaldor-Hicks approach captures the underlying intuition of the Pareto criterion but allows for some individuals to be made worse off by a given policy. A policy therefore yields a Kaldor-Hicks improvement if there is a "potential" Pareto improvement. Why is the mere possibility of a Pareto improvement appealing to a social planner? Proponents of the pure Kaldor-Hicks approach address this question in a few ways. First, many equate it with wealth maximization (see, e.g., Kaplow and Shavell, 2006; Kornhauser, 2003; Heinzerling, 2006). Regulations should singularly focus on the maximization of total resources. Redistribution should then occur through tax and transfer programs, which are better designed for redistribution than the regulation itself.[15] For this reason, pure Kaldor-Hicks benefit-cost analysis is often described as a measure of efficiency. However, this claim is disputed on two lines.

First, there is the basic premise that Kaldor-Hicks benefit-cost analysis indeed maximizes total wealth. However, Hemel (2022) argues that it excludes changes in total wealth that arise purely from changes in the distribution of income (Hemel, 2022). The equation between the Kaldor-Hicks approach and wealth maximization depends on the assumption that utility is weakly separable between leisure and private and public goods. As Boadway and Keen (1993) observe, when individuals switch from labor to leisure in the presence of a distortionary tax, total wealth decreases. This is commonly known as deadweight loss. Kaldor-Hicks benefit-cost analysis does not count deadweight loss as a cost. Hicks anticipates this point in his original paper:

> Since almost every conceivable kind of compensation (re-arrangement of taxation, for example) must itself be expected to have some influence on production, the task of the welfare economist is not completed until he has envisaged the total effects of both sides of the proposed reform. (Hicks, 1939)

[15] This assertion originated from a series of articles by Louis Kaplow and Steven Shavall arguing that the income tax system could redistribute better than legal reviews. It has since become a tenet of law and economics, appearing in a commonly used introductory textbook to law and economics: "The legal system is not nearly as precise as the tax system in redistributing income among the income classes" (Polinsky, 2011).

Advocates of the pure Kaldor-Hicks approach accept this point and argue that it still provides a practical approximation of wealth maximization. It is often ambiguous whether a public good is a complement to labor or leisure. For example, providing low-income individuals with public goods that are complementary to labor (e.g., public transit) may result in less deadweight loss than cash transfers, whereas providing public goods that are complementary to leisure (e.g., public bike paths) may result in more deadweight loss than cash transfers (Makridis, 2015). It is therefore unclear whether we should choose more or less redistributive policies when the weak separability assumption does not hold. As Hicks (1939) concludes, "it is not very surprising to find that some of the fine points in welfare theory are nothing but snares."

Second, there is the argument that tax and transfer programs are better designed for redistribution than regulation itself. Revesz (2018) argues that this view suffers from two serious shortcomings: one conceptual and one political.[16]

The conceptual shortcoming is directly relevant to the case at hand: the income tax regime is poorly suited to compensate individuals for loss of life. The tax system generally redistributes on an ex post basis, considering losses and gains already realized rather than those that might come to be (Revesz, 2018). On the other hand, these sorts of risk calculations are commonplace for regulatory agencies like the EPA. If the tax system cannot do redistributive work well in the context of non-monetary harms, the focus should turn back to the regulatory process itself—namely, by including distributional concerns directly in benefit-cost analysis.

On the political front, distribution through the tax system is premised on the notion that Congress will in fact act to provide the necessary distributional adjustments to the tax system. Even if the income tax system was well-equipped to address nonmonetary harms through redistribution, it is unlikely that our gridlocked Congress would be able to put such a tax into effect (Revesz, 2018). Because of this concern, Arrow et al. (1996) argue that a more stringent version of the Kaldor-Hicks principle should ask whether compensation is

[16] Note that Revesz is now the head of the Office of Information and Regulatory Affairs (OIRA), the agency tasked with the overhaul of benefit-cost analysis in the Biden administration.

likely to occur rather than whether it could possibly occur.

Hemel (2022) provides an additional political shortcoming of the pure Kaldor-Hicks approach: agency procedures that send a message to some that their lives are worth less have the potential to be harmful on the political front. I return to this point in greater detail in my normative analysis.

Despite this body of criticism, the Kaldor-Hicks criterion remains the theoretical underpinning of the federal government's approach to benefit-cost analysis and therefore its approach to the estimation of the SCC (EPA, 2022). One can derive the rationale for the use of a country-level VSL in the estimation of the SCC from the Kaldor-Hicks criterion. In order to determine potential Pareto improvements, one needs an estimate of an individuals' willingness to pay. Agencies use the VSL to estimate individuals' willingness to pay for avoided premature mortality risk. Since it would be impossible to measure each individual's VSL, agencies start with a central VSL estimate and then use a "benefits transfer" approach to infer VSL as a function of per capita income and income elasticity. An income elasticity of one implies that a one percent increase in per capita income yields a one percent increase in VSL. The benefits transfer approach is applied at the country-level for the estimation of the SCC. In short, under pure Kaldor-Hicks benefit-cost analysis, the value applied to premature deaths is constructed using a country-level approximation of individuals' willingness to pay for avoided mortality risks.

3.1.2 Domestic status quo

The domestic status quo approach is identical to the pure Kaldor-Hicks approach in all respects but one: instead of monetizing premature mortality using an income elastic VSL, it assigns a single population-wide value to all premature deaths in the US. Whereas the Kaldor-Hicks criterion values all benefits and costs based on willingness to pay, status quo benefit-cost analysis assigns the same VSL regardless of income. In other words, agencies value mortality risk reductions in Mississippi the same as in Connecticut. If the EPA had extended the logic of the domestic status quo approach to the estimation of SCC, they would have used a global average VSL for the monetization of premature mortality risk.

Domestic status quo benefit-cost analysis has indeed been the "status quo" for the past 20 years. McGartland (2021) explains that using a single uniform VSL "allows agencies to avoid difficult communications covering this controversial issue." However, federal agencies' practice of assigning uniform VSLs across populations—while appealing on ethical, political, and legal grounds—represents a clear diversion from the Kaldor-Hicks criterion. The pure Kaldor-Hicks approach relies on estimations of individuals' willingness to pay. But the status quo approach uses a US population average estimate of willingness to pay. A policy that passes the Kaldor-Hicks criterion may not be net beneficial under the domestic status quo approach, and vice versa.

Consider, for example, an agency's decision of whether to allow the construction of a polluting plant upwind of a low-income community (Bressler and Heal, 2022). The primary cost of the plant is premature mortality in the low-income community, which would be valued at $5 million under the pure Kaldor-Hicks approach, but roughly $11 million under status quo approach. If the net benefits of the plant were $6 million, the rule would pass Kaldor-Hicks benefit-cost analysis but not status quo benefit-cost analysis. On the other hand, if the same plant were to neighbor a high-income community, the opposite could be true. Status quo benefit-cost analysis may consider a policy net beneficial regardless of whether or not the winners of the policy (in our case, the factory's shareholders) could potentially compensate the losers (the downwind community).

The domestic status quo approach may not be consistent with the Kaldor-Hicks criterion any time a given benefit-cost analysis includes the monetization of mortality damages—which is a majority of the time. Historically, 70% of the total benefits in benefit-cost analyses of federal regulations were directly attributable to the monetized value of reducing premature mortality (Colmer et al., 2020). Moreover, 85% of the benefits from the Clean Air Act Amendment were attributable to a reduction in premature mortality (EPA, 2011).

It is worth stressing that status quo benefit-cost analysis does not directly correspond to any normative principle: it is not a measure of efficiency nor is it a measure of welfare, since welfare depends on distribution. As Hemel (2022) notes, while the task of federal agencies is not to implement "abstract theories of the good," domestic status quo benefit-cost analysis does start on shaky theoretical ground.

While the lack of conceptual clarity in status quo benefit-cost analysis is not a fatal flaw in itself, Sunstein (2004) presents two compelling arguments against the approach when the beneficiaries of a regulation must pay for all of its costs. Agencies' use of a population-average VSL means that low-income individuals are implicitly forced to buy protection against statistical risks at a much higher price than their willingness to pay. Sunstein refers to such practice as a "forced exchange." For example, the Department of Transportation might justify an increase in automobile safety standards using an average VSL of $11 million. While this regulation may be welfare improving for the average individual, low-income individuals may be forced to buy vehicles with more expensive safety features than their willingness to pay to avoid the decreased mortality risk. This regulation would therefore lead to a decrease in welfare.

In addition to decreasing welfare, Sunstein (2004) argues that "forced exchanges" violate consumers' autonomy: "people should be sovereign over their own lives, and the government should respect personal choices about how to use limited resources." McGartland (2021) asserts that benefit-cost analysis should be based on consumers' values, not what a policy maker in Washington thinks the benefits and costs are worth.

However, these so-called "welfare" and "autonomy" arguments do not apply when the beneficiaries of a regulation pay only a fraction of its costs (Sunstein, 2004). Consider the same Department of Transportation example as above except now the cost of improved safety features are not passed onto consumers. The safety features are welfare-improving for all drivers regardless of their true VSL. Further, it does not insult anyone's autonomy to give them a good on terms they would find acceptable. This nuance leads Sunstein (2004) to conclude that regulators' approach to the monetization of premature mortality must be based on the scientific and economic specifics of a given regulation, most importantly whether the beneficiaries of a regulation are responsible for paying its costs:

> It is therefore reasonable to reject the confident view of economically inclined analysts who believe that accurate VSLs, based on actual willingness to pay, should always be the basis of regulatory policy. But it is similarly reasonable to reject the confident view of skeptics who believe that a uniform VSL, refusing to make distinctions among persons, is best on distributive grounds.

3.1.3 Equity weighting

Equity weighted benefit-cost analysis estimates willingness to pay in market dollars and then applies weights to account for diminishing marginal utility of consumption. In the climate economics literature, equity weights are typically chosen to reflect empirical estimates of the diminishing marginal utility of consumption across individuals. I present the analytical basis for equity weighting in the social welfare function in further detail in Section 4. The basic idea is that marginal climate damages at a given time and place are weighted by the discounted marginal utility of consumption. Weighted marginal damage estimates are then summed over time and space to arrive at an aggregate measure of marginal damage expressed in units of utility. This is what legal scholars refer to as "hard-weighting." "Soft-weighted benefit-cost analysis constructs weights to achieve some distributive goal rather than matching an empirical estimate of diminishing marginal utility (Sunstein and Hahn, 2001). I focus on the hard-weighted approach given its dominance in the climate economics literature.

A useful analytical fact for comparing equity weighting benefit-cost analysis to status quo benefit-cost analysis emerges from the hard-weighted approach: the weights that account for diminishing marginal utility of consumption offset the differences in willingness to pay to avoid mortality. In other words, equity weighted benefit-cost analysis reflects that willingness to pay differs by income, but also that the value of a marginal dollar of income also differs by income. This can result in assigning equal value to the benefits of avoided mortality risk under the status quo and equity weighted approaches. More precisely, the mortality partial

SCC using a global average VSL is equivalent to the equity weighted mortality partial SCC under a set of assumptions.[17] Both approaches accord equal value to all statistical lives: the former in market dollars and the latter in welfare units.

Proponents of an equity weighted SCC prefer it over the status quo approach because it accounts for diminishing marginal utility in the calculation of all benefits rather than just avoided premature mortality risk. In fact, for low-income individuals, a global extension of the status quo approach overestimates avoided premature mortality risk relative to other benefits because mortality benefits are upweighted while all other benefits are measured in terms of willingness to pay (Bressler and Heal, 2022).

Another appealing characteristic of equity weighted benefit-cost analysis relative to the status quo approach is that it can be justified by the Kaldor-Hicks criterion though it does not take the Kaldor-Hicks criterion as a first principle. Equity weights simply transform market dollars into welfare units. If the weighted benefits of a policy exceed the weighted costs, the winners of the policy could compensate the losers with their surplus equity weighted dollars.

A critique of equity weighting that also applies to benefit-cost analysis more broadly is the need to account for the deadweight loss resulting from redistribution. If weighted benefit-cost analysis counts an increase in redistribution as a welfare gain, then it should acknowledge the corresponding increase in deadweight loss as a welfare loss. Critics argue that without accounting for adjustments in individuals' labor supply in response to redistribution, equity weighted benefit-cost analysis counts the benefits of redistribution but not the costs (Hemel, 2022). However, as noted above, it is often unclear whether a public good is a complement to labor or leisure, which makes the task of accounting for deadweight loss difficult–and somewhat arbitrary–in practice. Applications of weighted benefit-cost analysis generally do not account for this fact.[18]

[17] See Section 4.

[18] The UK Green Book, for example, does not account for deadweight loss resulting from the labor-leisure trade-off (HM Treasury, 2022).

3.2 Normative implications for the estimation of the SCC

In this section, I move from descriptive to normative analysis to respond to the two questions presented above: (1) Should agencies retain their commitment to equal-dollar VSLs at all income levels and (2) Should agencies continue to use distribution neutral benefit-cost analysis? My answers depend on the unique context of the estimation of the SCC, the first time benefit-cost analysis has included mortality impacts of a US policy on other countries. I ultimately defend an extension of the status quo to the global context, though reasonable readers may differ. My primary goal in this section is to clarify the trade-offs between each approach.

My argument proceeds in five sections. Section 3.2.1 considers whether the choice among the three approaches can be resolved on purely ethical grounds. If the tax system is optimal, the answer appears to be no. In theory, all three approaches accord equal value to all statistical lives. However, without an optimal taxation system, pure Kaldor-Hicks benefit-cost analysis does not accord equal value to all statistical lives. Section 3.2.2 discusses why the assumption of an optimal taxation system is flawed in the context of climate change, while Section 3.2.3 examines the consequences of this result. The arguments at this point defend the status quo or equity weighted approaches as the preferred modes of benefit-cost analysis. However, there are compelling arguments against the status quo approach, to which Section 3.2.4 responds.

The most important distinction between the status quo and equity weighting approaches is their answer to the second question presented above: whether benefit-cost analysis should continue to be distribution neutral or weighted. Section 3.2.5 presents several practical arguments in favor of a global extension of the status quo.

3.2.1 Equal value for all lives, conditional on optimal taxation

One virtue of the status quo approach is that it most visibly accords equal value to all statistical lives by assigning equal-dollar VSLs. Equity weighting next most visibly does so by yielding equal values for all statistical lives in welfare units.[19] On first glance, pure Kaldor-Hicks benefit-cost analysis appears to yield a different result. However, recall the discussion of weak separability. When the tax system is optimal and weak separability applies, pure Kaldor-Hicks benefit-cost analysis yields the same outcomes as equity weighted benefit-cost analysis. More precisely, when equity weights are inverse to income,[20] the income elasticity of VSL is equal to one, and there is consideration of both the welfare benefits of distribution and the associated deadweight loss, Kaldor-Hicks benefit-cost analysis yields the same policy prescriptions as equity weighted benefit-cost analysis (Hemel, 2022).

To illustrate, assume as most economists do that utilitarianism is the correct approach to normative analysis. Equity weighted benefit-cost analysis roughly approximates utilitarianism when utility is logarithmic in income (Hemel, 2022). Pure Kaldor-Hicks benefit-cost analysis does the same: if the tax system is optimal, the pure Kaldor-Hicks approach results in equivalence between the welfare gain from additional redistribution and the welfare loss from additional labor-leisure distortions.

In short, the ethical principle that all lives have equal value fails to resolve the debate among the three approaches. If the tax system is optimal, the choice can not be made on purely ethical grounds.

3.2.2 Optimal taxation is infeasible in the case of climate change

The key argument underlying the pure Kaldor-Hicks approach is that an optimal tax and transfer system is better designed for redistribution than regulation itself. If compensation were credible in the case of climate change, then using an income-elastic VSL to calculate the SCC could lead to potential Pareto improvements. Even though individuals in high-income countries are responsible for increased mortality risk in low-income countries, individuals in low-income countries would be compensated for the damages and all parties would be better

[19] Conditional on a few assumptions explained in Section 4.

[20] This is equivalent to Negishi weighting. See Section 4 for more details.

off.

However, the assumption that such compensation will occur is not credible. The OMB succinctly articulates this point in their rational for the revisions to Circular A-4, the document governing benefit-cost analysis:

> If it were possible to redistribute income from the winners to the losers using a costless, non-distortionary tax and transfer scheme, everyone could potentially be made better off (or no worse off) by a regulation for which there is a positive total net willingness to pay. However, this theoretical possibility is not likely to be realized or even approximated. As such, analyzing the full welfare effects of regulations requires analyzing the incidence, or distribution, of their effects. (OMB, 2023c)

Indeed, climate change is a case where the theoretical possibility of income redistribution is high unlikely to be realized or even approximated. The Intergovernmental Panel on Climate Change (IPCC) writes that full compensation for the contribution of domestic greenhouse gas emissions towards increased premature mortality risk "is conceptually difficult to estimate, and unlikely to occur" because "credit and risk-sharing markets are imperfect at the world level, global coordination is limited by agency problems, information is asymmetric, and no supranational tax authority can reduce worldwide inequalities" (Kolstad, 2014). In short, while arguments around compensation are contested yet plausible in the domestic context, they fall apart in the case of climate change. Some even argue that the assumption of compensation is implausible because of "gridlock in Congress" (Revesz, 2018). Yet there is still a functional tax and transfer system in the domestic context. Gridlock in Congress pales in comparison to the 30-year impasse on international climate negotiations that has yielded voluntary agreements as its primary means of compensation.

The controversy around Loss and Damage at the 27th United Nations Conference of the Parties exemplifies this claim. Loss and Damage includes non-economic loss and damage, such as loss of life. While the agreement to create a Loss and Damage fund was historic, participation in the fund is also completely voluntary. It is still unclear what types of activities it will support, how it will be governed, which countries will be eligible to receive support, and which countries will contribute. A best case scenario for the Loss and Damage fund is that it contributes a tiny fraction of the total compensation necessary for Pareto improvements in low-income countries.

3.2.3 Political consequences

The pure Kaldor-Hicks approach does not assign equal value to all statistical lives in the context of climate change. I now consider how individuals may perceive this result and the consequences of public perception on the regulatory process. First, there are the public relations concerns. Journalists read regulatory impact analyses and Federal Register notices and typically simplify the finer points. Before deciding to use lower-dollar VSLs for low-income individuals, the EPA should think carefully about the consequences of news headlines declaring that it discounts low-income individuals' lives, particularly given the centrality of the SCC to all executive branch climate rulemaking. As of this writing, *Vox* has published a piece titled "The tricky business of putting a dollar value on a human life," while *NPR* has aired a segment on national radio titled, "EPA's proposal to raise the cost of carbon is a powerful tool and ethics nightmare" (Dylan Matthews, 2022; Hersher et al., 2023). An excerpt on Weekend Edition stated: "One climate-related death in the US has about as much value as nine deaths in India, or five deaths in Ukraine, or 55 deaths in Somalia." The singular focus on the issue of income-elastic VSLs severely undermines the vast body of good work that went into the EPA's update to the SCC.

But the concern should not purely be about public relations. A second potential consequence is that the government may be viewed as having a lack of concern for low-income individuals' interests. It is undeniably a bad thing if millions of Americans think that the federal government discounts the lives of low-income individuals—hence agencies' adherence to the status quo approach for domestic benefit-cost analysis. The utility we derive from trust in the federal government is a difficult-to-quantify but non-trivial value (Hemel, 2022).

The use of different-dollar VSLs has resulted in both kinds of these perceptive consequences in the domestic and international contexts. On the domestic side, a 2002 Bush administration proposal used a VSL of \$3.7 million for the general population and a VSL of \$2.3 million for seniors. Even though the proposal actually assigned a higher value to avoided deaths for seniors after it adjusted for the value per life year,[21] the National Resources Defense Council and other environmental groups seized on the opportunity to oppose the proposal, which the administration had embraced over an alternative that would have led to faster air quality improvements (Revesz, 2018). Protesters in Tampa, Pittsburgh, Iowa City, San Antonio, and Los Angeles opposed the EPA's "senior death discount" (Skrzycki, 2003). In May 2003, EPA administrator Todd Witman discontinued the use of age-adjusted VSLs (Tierney and Seelye, 2003).

On the international side, in 1995 the IPCC faced a starkly similar controversy to the one at hand. A draft of Chapter 6 of the IPCC Second Assessment Report (AR2) used an income-elastic VSL to quantify mortality damages (Grubb, 2005). There was significant backlash at the plenary session during which government delegates from all of the UNFCCC Parties discussed the Summary for Policymakers, a 30 page summary of the approximately 1,000 page report. The delegates perceived the chapter's use of an income-elastic VSL as meaning that each person killed by climate change in a low-income country accounted for a fraction of each person killed in a high-income country (Grubb, 2005). The environmental minister of India called the approach "absurd and discriminatory" and for it to be "purged from the process" (Bressler and Heal, 2022). Delegates from India were joined by delegates from China, Cuba, Brazil and Peru in calling for a common valuation of all lives based on the highest number estimate for willingness to pay (Pearce, 1995).

However, David Pearce, the lead convening author of the chapter, refused to change the chapter's methodology.[22] In the end, the Summary for Policymakers implicitly rejected the

[21] The agency had applied a premium of approximately 58% for seniors after adjusting for the value of a statistical life year (VSLY).

[22] In a correction article, Pearce states, "You report that 'the economists were told to go back and do their work again': no such request was made nor could it have been honoured anyway since (a) the chapter had already undergone two peer reviews, (b) IPCC delegates (mainly political appointments) have no power to request authors to change already accepted chapters, and (c) ownership of the chapters rests with the authors, not the IPCC" (Pearce, 1995).

chapter's approach. According to Michael Grubb, another lead author of the report, "the resulting confrontation came closer than anything else to wrecking the IPCC" (Grubb, 2005). Pearce became the first and only IPCC convening lead author to have officially dissented from a chapter for which he was responsible (Grubb, 2005). Grubb later wrote:

> Many of us think that the governments [India, China, etc.] were basically right. The metric [used by Pearce] makes sense for determining how a given government might make tradeoffs between its own internal projects. But the same logic fails when the issue is one of damage inflicted by some countries on others: why should the deaths inflicted by the big emitters—principally the industrialized countries—be valued differently according to the wealth of the victims' countries? (Grubb, 2005)

This point adds a further dimension to my analysis of political consequences that intersects with the discussion in the following section. The logic for income-elastic VSLs fails when those who benefit from emissions are not the same as those paying for emissions reductions. In these cases, assigning different-dollar VSLs to individuals with different incomes may undermine the practice of benefit-cost analysis itself.

Following this controversy, the Third Assessment Report (AR3) used a global VSL based on the VSLs in the EU and US. The logic in this senior essay follows closely with the logic articulated by the IPCC:

> The VSL is generally lower in poor countries than in rich countries, but it is considered unacceptable by many analysts to impose different values for a policy that has to be international in scope and decided by the international community. In these circumstances, analysts use average VSL and apply it to all countries. Of course, such a value is not what individuals would pay for the reduction in risk, but it is an 'equity adjusted' value, in which greater weight is given to the willingness to pay of lower income groups. (IPCC, 2001)

The public relations concern alone is not significant enough to resolve the income-differentiated VSL debate. Indeed, it may not even be justified. Americans may protest at the thought of low-income or older Americans' lives being discounted, but they may have no qualms with discounting the lives of low-income individuals in other countries. Indeed, many argued that the SCC should only include domestic damages—which in effect completely discounts damages to all individuals outside the US (The White House, 2017). That said, the previous experience of the IPCC with different-dollar VSLs should prompt serious consideration about the use of an income-elastic VSL in the SCC, which may undermine the US in international climate negotiations.

3.2.4 The majority of the beneficiaries of emissions reductions do not pay for emissions reductions

Taken together, the arguments thus far point to the status quo or equity weighting as the preferred approaches for the updated SCC. However, as discussed in the descriptive analysis of the status quo approach, there are compelling arguments against it when the beneficiaries of a given regulation are responsible for all of its costs: using a population-average VSL has the potential to infringe upon consumer sovereignty and decrease welfare. In these "easy cases," social harm will almost inevitably result from the application of a uniform VSL.

This section responds to the consumer sovereignty and welfare arguments on the grounds that the beneficiaries of emissions reductions do not pay for their costs. Indeed, the case at hand is a "hard case" in Sunstein's typology. In these cases, a uniform VSL may be in low-income individuals' interests because it increases redistribution. Sunstein (2004) states:

> A poor nation would do well to adopt a lower VSL than a wealthy nation; for China or India, it would be disastrous to use a VSL equivalent to that of the United States or Canada. But this point should not be taken to support the ludicrous proposition that donor institutions, both public and private, should value risk reduction in a wealthy nation above equivalent risk reduction in a poor nation.

The US government is a public donor institution in the case of the SCC. Neither the consumer sovereignty nor welfare arguments hold for individuals outside of the US since these individuals do not have to pay for any regulation influenced by the SCC. One could argue, however, that the consumer sovereignty of individuals in the US is violated because a global average VSL is less than their willingness to pay to avoid mortality risk. Such arguments may prompt the use of a "high-income country" VSL following the IPCC AR3 approach (IPCC, 2001).

That said, consumer sovereignty must be considered together with welfare. Given that the most severe mortality impacts of climate change will occur in low-income countries, moving from a country-level to a global average VSL increases the SCC. For individuals in the US, the consumer sovereignty and welfare arguments work in opposite directions. Taking the consumer sovereignty argument alone would suggest that the SCC undervalues US individuals' willingness to pay, but the SCC increases with the use of a global average VSL. Of couse, the SCC would increase by much more using a "high-income country" global VSL aligned with US willingness to pay. But applying a VSL orders of magnitude higher than low-income individuals' "true" VSLs then runs into the issue of economic efficiency. An SCC this large may direct the US to overinvest in climate change mitigation relative to other pressing issues.

3.2.5 Practical concerns with equity weighting

The most important distinction between the two remaining approaches is their stance towards weighting. This section presents a practical defense of the distribution neutral approach (i.e., the status quo) for immediate use in the EPA's updated SCC. That said, I hold that equity weighting remains the first-best approach from a conceptual perspective. Further, given OMB's recently proposed updates to Circulars A-4, equity weighting may be permitted in future benefit-cost analyses (OMB, 2023a,b). At the same time, however, there are several concerns with the immediate implementation of equity weighting in the updated SCC.

First, there is uncertainty about the correct value to use for the elasticity of marginal utility. Legal scholars speculate that any choice of a social welfare function could prove controversial and be the focus of challenges in court (Revesz and Yi, 2021). The draft revisions to Circular A-4 posit that 1.4 is a "reasonable" default estimate of the elasticity of marginal utility based on a survey of empirical evidence (OMB, 2023a,c; Acland and Greenberg, 2022). However, the estimates cited vary widely and come from a variety of literatures. Studies of risk aversion find values between 0.7 and 1.8; studies on subjective well-being find values between 1.2 and 1.39; and studies on the VSL elasticity find values between 0.5 and 1.44 (OMB, 2023c).

More fundamentally, directly incorporating distributional weights in the social welfare function through equity weighting represents a wholesale overhaul of a regulatory review process with which courts have become familiar (Revesz and Yi, 2021). The draft revisions to Circular A-4 may be met with significant push back during the public comment and peer review process. They could also be reversed in a future administration.

Finally, the default versions of the damage functions used to calculate the SCC are not equity weighted (Carleton et al., 2022; Moore et al., 2017; Diaz, 2016; Cromar et al., 2022). If equity weighting becomes the default approach in the climate economics literature—and it is still permitted in a future version of Circular A-4—there is no question that it will be the first-best approach. But given the intense legal scrutiny already placed on the SCC, a departure from the published versions of the damage functions used to calculate it may be the subject of legal challenge.[23]

A global extension of the status quo approach, however, marks less of a departure from the default versions of the damage functions used to calculate the SCC. One of the two papers that includes mortality damages in the Howard and Sterner (2017) meta-analysis globally applies the VSL for OECD nations (Meyer and Cooper, 1995).[24] In addition, Carleton et al. (2022) use a global average VSL as an alternative specification.

More importantly, however, the status quo approach has undeniable precedent in past regulatory practice. Sunstein (2004) writes:

> To conduct cost-benefit analysis, agencies must assign monetary values to human lives that are potentially saved by a proposed regulation. How do they come up with the numbers that they use? Do some deaths count for more than others?...No agency values the lives of poor people less than the lives of rich people. No agency distinguishes between whites and African Americans or between men and women. For statistical lives, the governing idea is that each life is worth exactly the same. With respect to cost-benefit analysis, much is disputed. But on the idea of a uniform value per life saved, there is a solid consensus, at least in terms of regulatory practice.

[23]Shortly after the IWG released its interim estimates, states' attorneys general brought two challenges against the estimates. In Missouri v. Biden, Missouri and 11 other states argued the imposition of the interim estimates violates constitutional separation of powers and federalism principles. In Louisiana v. Biden, Louisiana and nine other states argued that the interim estimates violate five environmental statutory provisions and constitutional principles, including the Major Questions doctrine (Revesz and Yi, 2021).

[24]Howard and Sterner (2017) undo this assumption in order to derive a corresponding willingness to pay estimate.

Further, the status quo approach is the explicit directive of the current version of Circular A-4 as well as the National Academies' guidance on updating the SCC (OMB, 2003; NASEM, 2017). Circular A-4 states, "When numeric adjustments are made for life expectancy or quality of life, analysts should prefer use of population averages rather than information derived from subgroups dominated by a particular demographic or income group."

In sum, an extension of the domestic status quo approach—using a global average VSL to calculate the SCC—offers somewhat of a middle ground for the updated SCC. This is not to say the status quo approach would not face legal challenges of its own. The status quo approach has never been applied to valuing lives outside of the US. It reflects a departure from precedent in a similar manner to how the Obama-era SCC's inclusion of global and not merely domestic damages reflected a departure from precedent. That said, using a global average VSL is most consistent with the logic behind the EPA's approach to benefit-cost analysis. Ever since the senior death discount controversy, the EPA has used a single value to monetize premature mortality risk. Why should it change its approach simply because it is monetizing premature mortality outside of its borders? Put differently, if the EPA values Rhode Island deaths the same as Texas deaths, why shouldn't it value Russian deaths the same as Ukrainian deaths? The status quo approach offers an appealing pathway to avoid the political and ethical consequences associated with different-dollar VSLs without necessitating an overhaul of the process of estimating the SCC.

3.3 A response to the EPA's approach

This section extends the normative analysis above to directly respond to the EPA's justification for using an income-elastic VSL in the updated SCC. They emphasizes two points, to which I respond in turn.

The EPA writes that their approach "is consistent with the benefits transfer approaches used in the default versions of the published studies used to calculate the SCC" (EPA, 2022). This is indeed true,[25] and it causes a dilemma for the EPA: should it be consistent with the published studies it has used to calculate the updated SCC or with all previous domestic benefit-cost analysis? I argue for the latter. The EPA is already grappling with the consequences of using an approach that does not accord equal value to all statistical lives. Further, most climate economic studies using an income-elastic VSL to monetize premature deaths start from an entirely distinct first principle. Rather than justifying the benefits-transfer approach based on the need to estimate willingness to pay in order to apply the Kaldor-Hicks criterion, they apply the benefits-transfer approach in line with the theory of revealed preferences. That said, the EPA's desire for consistency with the studies it uses in its updated estimates is acceptable. Government metrics should use the best available science. If the primary goal is consistency with these studies, then the EPA's approach is justified.

But consistency with the literature is not the EPA's singular concern. In fact, the primary defense of their approach is consistency "with the Kaldor-Hicks criterion that underlies all other elements of the EPA's benefit-cost analysis" (EPA, 2022). This is the claim which I most clearly oppose. I break my counterargument into two parts.

First, there is the claim that their approach is "consistent with the Kaldor-Hicks criterion." However, the Kaldor-Hicks criterion only holds if benefit-cost analysis is conducted using units of money that represent an actual unit of exchange. The income projections used to calculate the SCC are based on purchasing power parity (PPP)—a hypothetical numéraire—instead of market exchange rates (Bressler and Heal, 2022). Although PPP converts money into units that are more relevant to what a social planner would normally care about, this conversion undermines the appeal to the Kaldor-Hicks potential compensation criterion (Bressler and Heal, 2022). PPP-based dollars are between 2 and 4 times higher than market dollars in most low-income countries (Callen, 2007). Using market dollars may therefore significantly

[25]There are two caveats to note here. First, Carleton et al. (2022) value statistical lives proportionally to 24,378 regions. Second, Carleton et al. (2022) use an age-varying VSL approach. Their main specification is therefore not exactly consistent with the EPA's approach which uses an age-invariant, country-level VSL. Regardless, in both cases, the EPA's approach is consistent with that of Carleton et al. (2022) in that they both use benefits-transfer.

lower the SCC given the majority of damages are occurring in these countries. Indeed, one could adjust the PPP-based potential transfers to market dollars, but such adjustments are time and labor intensive and for this reason unlikely to occur in practice. Further, making such adjustments would cause the EPA's approach to stray from the default versions of the published studies, which contradicts its other objective.

The second part of the EPA's claim is that the "Kaldor-Hicks criterion underlies all other elements of the EPA's benefit-cost analysis." Though the Kaldor-Hicks criterion underlies the EPA's benefit-cost analysis, for the past twenty years all domestic benefit-cost analyses have assigned an equal dollar value to all statistical lives regardless of income. It is likely that a majority of past benefit-cost analyses were not consistent with Kaldor-Hicks since 70% of net benefits have come from reductions in premature mortality risk (Colmer et al., 2020). Using a global average VSL is far more consistent with past practice.

Then there is a final, more fundamental question that the EPA itself does not ask: is the Kaldor-Hicks criterion one worth being consistent with? In the context of monetizing the mortality impacts of climate change, the rationales for adhering to the Kaldor-Hicks do not apply. There is no supranational tax authority—or even systematic voluntary mechanism—to redistribute income such that individuals in low-income countries bearing the brunt of climate damages are compensated for the excess deaths caused by US emissions.

4 Theoretical model

This section formally describes the three approaches to calculating the SCC. The derivation of the SCC in welfare units is identical across the three approaches. They only differ with respect to monetization. I use the notation developed in Anthoff et al. (2009) and Bressler and Heal (2022) throughout this section.

Before presenting the model, it is worth noting the distinction between utility-based and output-based models (Nordhaus, 2011). Models such as RICE are utility-based, meaning that they evaluate a social welfare function. Utility-based models therefore explicitly include an equity weighting parameter η. A second group of models, of which GIVE is an example, are output-based. Output-based models are a special class of utility-based models, where the consumption elasticity of marginal utility (η) is 0. Equity weighting of these models must therefore occur during monetization. Output-based models simply calculate the present value of the discounted sum of damages over time and space. Note that there is no mention of a social welfare function in EPA (2022). Government agencies take the Kaldor-Hicks criterion as first-principle instead of a social welfare function (IWG, 2016, 2021; EPA, 2022). I keep my notation general in this section to show how each of the three approaches apply in utility-based or output-based models.

I derive the SCC for each approach using a social welfare function framework even though the GIVE model is output-based and therefore does not explicitly rely on a social welfare function. I do this for a few reasons. First, the assumption of a discounted utilitarian framework is an ethical choice and not an empirical one. This assumption is not made explicit in Rennert et al. (2022), but it is important to be clear about given the criticism of the discounted utilitarian framework and proposed alternative social welfare functions. Second, equity weighting assumes a social planner and a social welfare function. The social planners' perspective is crucially important. Different national decision makers may have different perspectives and choose different equity weights. Equity weights do not reconcile these different positions—they merely make such concerns explicit (Anthoff et al., 2009). Finally, working from a social welfare function reveals important theoretical relationships between each of the three approaches. Section 2 discussed the "two branches" of welfare economics that vary with respect to their stance on interpersonal comparisons of utility. I show that these branches may not be so distinct in practice due to the application of Negishi weights (Negishi, 1960).

4.1 The social welfare function

The standard social welfare function in climate economics captures the intuition that the individual marginal utility of consumption is decreasing with increasing consumption c. This intuition is expressed by an isoelastic utility function:

$$U(c) = \frac{c^{1-\eta}}{1-\eta}, \tag{4}$$

where η is the consumption elasticity of marginal utility. The social welfare function aggregates individual utility across a population of individuals $i = 1, ..., N$ at time t from $t = 1, ..., T$, the end of the planning horizon: (Anthoff and Emmerling, 2019; Nordhaus, 2011; Anthoff et al., 2009)

$$W = \sum_{i=1}^{N} \sum_{t=1}^{T} U(c_{it}) r_t, \tag{5}$$

where c_i is consumption of individual i and r_t is the utility discount factor. There are a wide variety of potential discounting procedures that can be captured by r_t.[26] I follow the standard Ramsey-style discounting methodology as it is the most established and widely used framework in regulatory analysis. This approach links the discount rate to future economic growth as $r_t = \rho + \eta g_t$, where ρ is the pure rate of time preference. The uncertainty in the discount rate leads to a stochastic discount factor, which can equivalently be written as (Newell et al., 2022; Rennert et al., 2022):

$$r_t = \frac{U'(c_{it})}{U'(c_{i1})} \frac{1}{(1+\rho)^t} = \left(\frac{c_{it}}{c_{i1}}\right)^{-\eta} \frac{1}{(1+\rho)^t}, \tag{6}$$

where the second equality follows from the isoleastic utility setting. Note that η takes on two meanings as (1) the parameter of risk aversion and (2) the parameter of intertemporal

[26] For example, some have proposed discount rates that consider epistemic uncertainty as well as alternative preference structures including ambiguity aversion (Berger and Marinacci, 2020).

substitutability of consumption, or inequality aversion. I consider both of these meanings in turn.

First consider η as the parameter of risk aversion. Deterministic models such as FUND do not explicitly include uncertainty and so η does not act as a parameter of risk aversion.[27] However, GIVE considers uncertainty about future consumption and therefore also treats η as the parameter of relative risk-aversion. Such a model may be written as:

$$\mathbb{E}[W] = \sum_{i=1}^{N} \sum_{t=1}^{T} U(c_{it}) r_t p_s \tag{7}$$

where s is a particular climate change scenario among a total of S scenarios, p_s is the probability of scenario s, and $\mathbb{E}[W]$ is now the expected value of welfare.

Now consider η as the parameter of both intertemporal and spatial inequality aversion. Inequality aversion refers to the welfare loss from different levels of consumption among individuals. For example, $\eta = 0$ corresponds to inequality neutrality since an absolute change in consumption counts the same to a high-income individual and a low-income individual. As $\eta \to \infty$, achieving equality dominates any other objective (e.g., raising average consumption) since a change in the consumption of the poorest member of society always dominates consumption changes of others (Anthoff et al., 2009). Therefore a discounted utilitarian social welfare function with $\eta \to \infty$ is equivalent to a maximin social welfare function since equation 5 becomes $W = \min[U(c_i)]$. Values of η between these extremes correspond to various ethical positions.

To illustrate, consider the example of $\eta = 1$. The utility function becomes $U(c) = \log(c)$, which is the limit of equation 4 as η tends to one. In this case, the marginal utility of consumption $U'(c) = 1/c$. Suppose a high-income county has per capita consumption of 10 and a low-income country has per capita consumption of 1. A unit of damages in the

[27]For this reason, Nordhaus (2011) prefers to call the utility function constant relative inequality aversion (CRAI) in the deterministic context, as opposed to its common name as constant relative risk aversion (CRRA).

high-income country will therefore be valued at one-tenth of the value of damage in the low-income country.

4.2 Marginal damage of carbon dioxide emissions

The marginal change in consumption, or damage D_{it}, for an individual i at time t is from a marginal change in CO_2 emissions today $(t = 1)$ is

$$D_{it} = \frac{\partial c_{it}}{\partial E}. \tag{8}$$

The SCC is equivalent to the marginal damage caused by marginal CO_2 emissions:

$$\begin{aligned} \text{SCC} = \frac{\partial W}{\partial E} &= \frac{\partial \sum_{i=1}^{N} \sum_{t=1}^{T} U(c_{it}) r_t}{\partial E} \\ &= \sum_{i=1}^{N} \sum_{t=1}^{T} \frac{\partial U(c_{it})}{\partial c_{it}} \frac{\partial c_{it}}{\partial E} r_t \\ &= \sum_{i=1}^{N} \sum_{t=1}^{T} \frac{\partial U(c_{it})}{\partial c_{it}} D_{it} r_t. \end{aligned} \tag{9}$$

Equation 9 represents the marginal change in net present social welfare from a marginal change in emissions today. Note that this equation rests on the assumption of a marginal change in emissions. Under radical shifts in global climate policy, the approximation underlying equation 9 is inapplicable (Anthoff et al., 2009).

4.3 Monetization

The SCC calculated above must be expressed in market dollars in order to be used in benefit-cost analysis. I focus on two approaches to monetization: (1) Negishi weighting and (2) equity weighting (Bressler and Heal, 2022).[28] The SCC calculated under the Kaldor-Hicks

[28]Equity weighting is also referred to as "welfare weighting", but I use equity weighting for consistency with the majority of papers in the climate economics literature.

approach is equivalent to a particular kind of Negishi-weighted SCC, while the equity weighted SCC naturally corresponds with the equity weighted approach. The status quo SCC is a combination of the two approaches to monetization.

4.3.1 Kaldor-Hicks SCC

Negishi weights α_{it} are constructed to weight the utility of individual i by the inverse of their marginal utility (Negishi, 1960):

$$\alpha_{it} = \frac{1}{\frac{\partial U(c_{it})}{\partial c_{it}}}. \tag{10}$$

Negishi weights are used in regionally disaggregated integrated assessment models such as RICE (Nordhaus and Yang, 1996; Yang and Nordhaus, 2006) and MERGE (Manne et al., 1995), where weighting simulates the outcome of an efficient international market for CO_2 emissions.[29] While maximization of a utilitarian social welfare function (equation 5) tends to equalize marginal utility of consumption across individuals, Negishi weights have the unique property to preserve the initial distribution of income throughout dynamic models, allowing for exchange but not redistribution (Fenichel and Abbott, 2014). Some criticize the use of Negishi weights for inhibiting the redistribution of wealth between high-income and low-income countries (Stanton, 2011). Others defend their use for converting each individuals' utility function into consumption equivalent dollars according each individuals' own valuation of income—which is in this sense in line with the Kaldor-Hicks potential compensation criterion (Fenichel and Abbott, 2014; Hammitt, 2013).[30]

[29] I apply the same kind of "generalized" Negishi weight as applied in Bressler and Heal (2022). The Negishi weight α_{it} above equalizes the marginal utility of consumption of every individual in every time period to the marginal utility of consumption of a the reference person. This differs from the Negishi weight applied in Yang and Nordhaus (2006), which equalizes the marginal utility of consumption of individuals within each time period, but not *across* time periods. The Yang and Nordhaus (2006) Negishi weights differ again from the original construction in Negishi (1960), which considers only one time period. Applying the Negishi weight α_{it} described here is equivalent to setting $\eta = 0$. I thank Simon Lang for clarifying this point.

[30] They do so by dividing each agents' utility by their marginal utility of income at the optimum, a value that is smaller for wealthier agents than for otherwise identical poorer agents. (Fenichel and Abbott, 2014).

Applying Negishi weights of this form to the welfare-denominated SCC in equation 9 yields SCC_{KH}, the SCC under the Kaldor-Hicks approach:

$$\text{SCC}_{\text{KH}} = \sum_{i=1}^{N}\sum_{t=1}^{T} \alpha_{it} \frac{\partial U(c_{it})}{\partial c_{it}} D_{it} r_t = \sum_{i=1}^{N}\sum_{t=1}^{T} D_{it} r_t. \tag{11}$$

Integrating equation 11 over emissions E yields the Negishi-weighted social welfare function:[31]

$$W_{\text{KH}} = \int \frac{\partial W}{\partial E}\, dE = \int \sum_{i=1}^{N}\sum_{t=1}^{T} D_{it} r_t \, dE = \sum_{i=1}^{N}\sum_{t=1}^{T} c_{it} r_t. \tag{12}$$

Utility is now linear in consumption instead of concave in consumption; that is, a high-income person values a marginal dollar equivalently to a low-income person.[32] The net benefits of a policy are measured according to each person's own current dollar valuation of marginal consumption (i.e., in terms of their willingness to pay). A policy passes the Kaldor-Hicks potential compensation criterion if it leads to a positive change in the Negishi-weighted social welfare function.

4.3.2 Equity weighted SCC

Equity weights μ_{xt} convert the SCC from units of welfare into dollars by normalizing the utility of individual i using the marginal social utility of consumption today ($t = 1$) of a

[31] Note that this operation technically yields equation 12 plus some constant which I leave out for simplicity (Bressler and Heal, 2022).

[32] Since $U(c_{it}) = \frac{c_{it}^{1-\eta}}{1-\eta} = c_{it}$, which implies that Negishi weights implicitly assume that $\eta = 0$.

reference person x:[33]

$$\mu_{xt} = \frac{1}{\frac{\partial U(c_{x1})}{\partial c_{x1}}}. \tag{13}$$

It's clear that the choice of the numéraire, or what individual to use as the reference individual x, has a major impact on the impact of equity weighting on the SCC. Applying equity weights to the SCC in welfare units accounts for the curvature of utility function so r_t in this case is simply a function of ρ (Anthoff et al., 2009):

$$\text{SCC}_{\text{EW}} = \sum_{i=1}^{N}\sum_{t=1}^{T} \mu_{x1} \frac{\partial U(c_{it})}{\partial c_{it}} D_{it} \frac{1}{(1+\rho)^t} = \sum_{i=1}^{N}\sum_{t=1}^{T} \left(\frac{c_{x1}}{c_{it}}\right)^{\eta} D_{it} \frac{1}{(1+\rho)^t} \tag{14}$$

It can be seen here that Negishi weights are in fact a special case of equity weights: the Negishi-weighted version assumes that each individual has the same marginal utility of consumption in every time period as the marginal utility of consumption of the reference person (i.e., $\frac{\partial U(c_{it})}{\partial c_{it}} = \frac{\partial U(c_{x1})}{\partial c_{x1}}$)(Bressler and Heal, 2022). Again integrating equation 14 over emissions E yields an equity weighted social welfare function:

$$W_{\text{EW}} = \int \frac{\partial W}{\partial E}\, dE = \int \sum_{i=1}^{N}\sum_{t=1}^{T} \left(\frac{c_{x1}}{c_{it}}\right)^{\eta} D_{it} \frac{1}{(1+\rho)^t}\, dE = \sum_{i=1}^{N}\sum_{t=1}^{T} \left(\frac{c_{x1}}{c_{it}}\right)^{\eta} c_{it} \frac{1}{(1+\rho)^t} \tag{15}$$

As with the previous approach, a policy is seen as beneficial if it leads to a positive change in the equity weighted social welfare function.

[33]The approach followed in this paper is called the "intertemporal approach", which is favored over the "cross-sectional approach" followed in the past by Tol (1999) and several other authors. The main difference between the two approaches is the normalization factor. In the "cross-sectional approach", normalization is with marginal utility at time t of the world average individual, whereas under the "intertemporal approach" normalization is with the current marginal utility ($t = 1$) of a particular reference individual x. Under the intertemporal approach, equity weights are therefore correctly applied across space and time, rather than just across space (Anthoff et al., 2009; Nordhaus, 2011).

4.3.3 Status quo SCC

I motivate the status quo SCC by starting with the Kaldor-Hicks social welfare function W_{KH}. Following Bressler and Heal (2022), I define a new term, k_{it}, which includes all net benefits of a marginal emissions reduction in consumption-equivalents except for willingness to pay to avoid mortality risk, $p_{it}\text{VSL}_{it}$, where p_{it} is the probability of mortality risk for individual i at time t and VSL_{it} is the value of a statistical life for individual i at time t. The social welfare function under the status quo approach can therefore be written as

$$W_{\text{SQ}} = \sum_{i=1}^{N} \sum_{t=1}^{T} (k_{it} - p_{it}\text{VSL}_{xt}) r_t \tag{16}$$

where VSL_{xt} is defined as the central estimate for VSL in the US at time t, though the term can represent the VSL of any reference individual x. Analysts use a benefits-transfer methodology to extrapolate how a reference person's VSL will change over time based on their change in consumption using the VSL elasticity parameter ϵ:[34]

$$\text{VSL}_{xt} = \text{VSL}_{x1} \left(\frac{c_{xt}}{c_{x1}} \right)^{\epsilon}, \tag{17}$$

Substituting equation 17 into equation 16 and expanding r_t yields

$$W_{\text{SQ}} = \sum_{i=1}^{N} \sum_{t=1}^{T} \left(k_{it} - p_{it}\text{VSL}_{x1} \left(\frac{c_{xt}}{c_{x1}} \right)^{\epsilon} \right) \left(\frac{c_{xt}}{c_{x1}} \right)^{-\eta} \frac{1}{(1+\rho)^t} \tag{18}$$

[34] Note that this derivation differs slightly from that in Bressler et al. (2021) to accurate portray the fact that the status quo approach allows the US VSL to grow over time.

Under the assumption that individuals value statistical lives equally in welfare units ($\eta = \epsilon$), equation 18 can be further simplified:

$$\begin{aligned} W_{\text{SQ}} &= \sum_{i=1}^{N} \sum_{t=1}^{T} \left(\left(\frac{c_{xt}}{c_{x1}} \right)^{-\eta} k_{it} - p_{it} \text{VSL}_{x1} \right) \frac{1}{(1+\rho)^t} \\ &= \sum_{i=1}^{N} \sum_{t=1}^{T} k_{it} r_t - p_{it} \text{VSL}_{x1} \frac{1}{(1+\rho)^t} \end{aligned} \tag{19}$$

Intuitively, the reference individual's VSL grows with consumption at the same rate that future dollars are discounted due to consumption growth. Future mortality risk is only discounted by ρ.

Finally, compare W_{SQ} to W_{EW} with consumption decomposed into non-mortality and mortality equivalents:

$$W_{\text{EW}} = \sum_{i=1}^{N} \sum_{t=1}^{T} \left(\frac{c_{x1}}{c_{it}} \right)^{\eta} (k_{it} - p_{it} \text{VSL}_{it}) \frac{1}{(1+\rho)^t} \tag{20}$$

The benefits-transfer methodology is again used, this time to extrapolate the central estimate for VSL in the US ($10.95 million in 2019 US$) to that of individuals in other populations:

$$\text{VSL}_{it} = \text{VSL}_{x1} \left(\frac{c_{it}}{c_{x1}} \right)^{\epsilon}, \tag{21}$$

Substituting equation 21 into equation 20 and again setting $\eta = \epsilon$,

$$\begin{aligned} W_{\text{EW}} &= \sum_{i=1}^{N} \sum_{t=1}^{T} \left(\frac{c_{x1}}{c_{it}} \right)^{\eta} \left(k_{it} - \left(\frac{c_{x1}}{c_{it}} \right)^{-\epsilon} p_{it} \text{VSL}_{x1} \right) \frac{1}{(1+\rho)^t} \\ &= \sum_{i=1}^{N} \sum_{t=1}^{T} \left(\left(\frac{c_{x1}}{c_{it}} \right)^{\eta} k_{it} - p_{it} \text{VSL}_{x1} \right) \frac{1}{(1+\rho)^t}. \end{aligned} \tag{22}$$

Therefore, the mortality portion of the status quo social welfare function is equivalent to the mortality portion of the equity weighted approach. Similarly, the non-mortality portion of the status quo social welfare function is equivalent to the non-mortality portion of the

Negishi-weighted approach. This observation enables us to write the SCC under the status quo approach. First let D_{it} be decomposed into non-mortality damages D_{it}^{NM} and mortality damages D_{it}^{M} as calculated under the status quo approach:

$$D_{it}^{\text{NM}} = \frac{\partial k_{it}}{\partial E} \qquad D_{it}^{\text{M}} = -\frac{\partial p_{it}\text{VSL}_{x1}}{\partial E}. \tag{23}$$

Now the SCC under the status quo approach can be written as

$$\text{SCC}_{\text{SQ}} = \sum_{i=1}^{N}\sum_{t=1}^{T} D_{it}^{\text{NM}} r_t + \left(\frac{c_{x1}}{c_{it}}\right)^{\eta} D_{it}^{\text{M}} \frac{1}{(1+\rho)^t}. \tag{24}$$

It is worth noting that since the majority of damages in the updated SCC are mortality damages, the status quo SCC is in practice closer to the equity weighted approach than to the pure Kaldor-Hicks approach.

4.4 Spatial resolution

None of the integrated assessment models used to calculate the SCC work on an individual agent level. Impacts are instead calculated separately for different regions. GIVE calculates the majority of damages on the country-level, while other models use finer or coarser grids.[35] Let D_{rt} represent the marginal change in consumption, or damage, in a region r at time t from a marginal change in CO_2 emissions today, where R is the total number of regions considered. Let $\bar{c}_{rt}$ be average per capita consumption for region r at time t. Finally, monetization is done relative to a specific country or region x:

[35] The DSCIM model calculates damages for 24,378 regions that are about the size of a US county (Carleton et al., 2022), FUND calculates damages for 16 regions (Anthoff et al., 2009), RICE calculates damages for 10 regions (Yang and Nordhaus, 2006).

$$\mathrm{SCC}'_{\mathrm{KH}} = \sum_{r=1}^{R} \sum_{t=1}^{T} D_{rt} r_t \tag{25}$$

$$\mathrm{SCC}'_{\mathrm{EW}} = \sum_{r=1}^{R} \sum_{t=1}^{T} \left(\frac{\bar{c}_{x1}}{\bar{c}_{rt}} \right)^{\eta} D_{rt} \frac{1}{(1+\rho)^t} \tag{26}$$

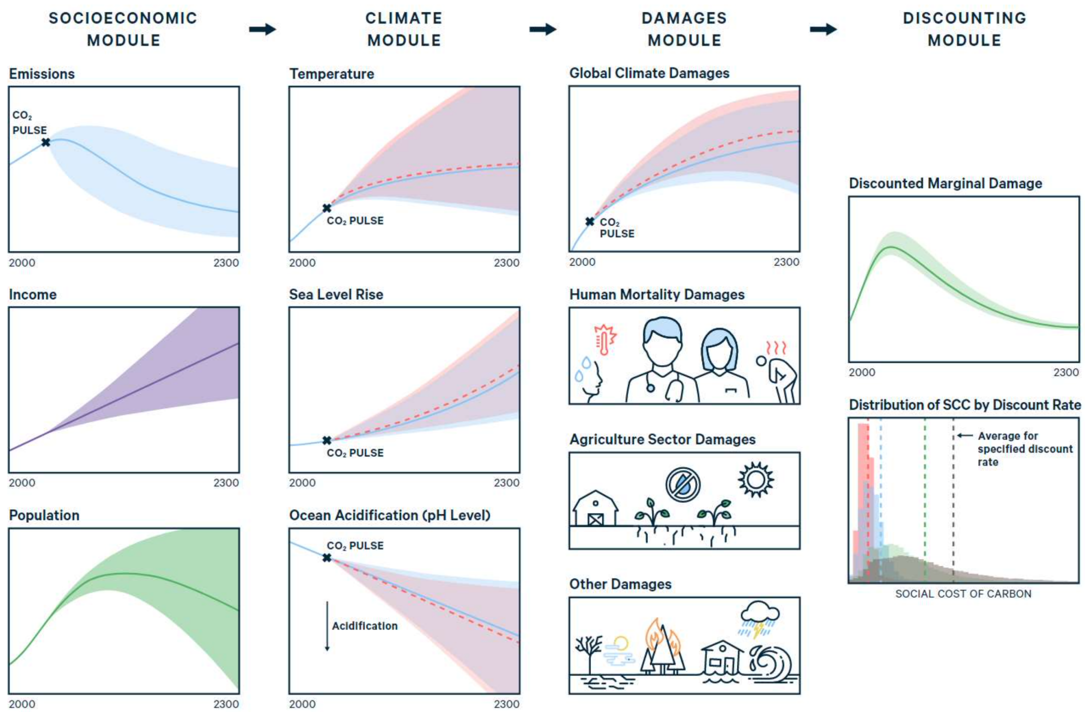
$$\mathrm{SCC}'_{\mathrm{SQ}} = \sum_{r=1}^{R} \sum_{t=1}^{T} D_{ct}^{\mathrm{NM}} r_t + \left(\frac{\bar{c}_{x1}}{\bar{c}_{rt}} \right)^{\eta} D_{rt}^{\mathrm{M}} \frac{1}{(1+\rho)^t} \tag{27}$$

An important consequence of aggregation to the regional level is that equity weighting no longer accounts for inequalities in consumption levels within countries despite the availability of data on per capita consumption at a far more detailed level (Anthoff et al., 2009; Fankhauser et al., 1997). Equation 26 now only accounts for inequalities in consumption levels between countries. This abstraction away from individuals' utility functions will occur with any level of aggregation though the theoretical inconsistency decreases in severity as spatial resolution increases.

5 Numerical model

This section implements each of the three approaches to calculating the SCC in order to assess the feasibility of their use by the US government. GIVE follows a four-step process to calculate the SCC: (1) projections of population and GDP drive a CO_2 emissions pathway; (2) the CO_2 emissions path informs a climate model that projects atmospheric greenhouse gas concentrations, temperature changes and other physical variables; (3) the resulting climate change impacts are monetized and aggregated as economic damages; and (4) all future damages are discounted into a single present value (Rennert et al., 2022). Figure 1 shows how each of these four steps are compartmentalized in a "module," enabling the incorporation of recent advances in the scientific and economic literature. GIVE's key contribution is the quantification of uncertainty in each component and the subsequent propagation of these compounding uncertainties throughout the computation.

Figure 1: Four modules for calculating the SCC



Source: Rennert et al. (2022)
Notes: Equity-weighting is not included in this diagram but occurs in the discounting module.

Sections 5.1.1-5.1.4 summarizes each of the four steps in the baseline GIVE model. Section 5.2 details my additions to the model in order to implement each of the three approaches to benefit-cost analysis. I make three important contributions. First, I add an additional temperature-related mortality damage function given several conceptual and econometric issues with the temperature-related mortality damage function used in Rennert et al. (2022). This does not alter the monetization of mortality risk but rather the estimate of mortality risk itself. An accurate estimate of mortality risk is just as important an appropriate monetization strategy. Second, I add flexibility to the VSL component of the damages module in order to calculate the SCC with an income-elastic VSL or a global average VSL. Third, I implement equity weighting in the discounting component. Finally, Section 5.3 describes the process for estimating the SCC as well as the Monte Carlo approach for sampling interrelated uncertainties.

5.1 The baseline GIVE model

5.1.1 Socioeconomic projections

The GIVE model samples the Resources for the Future Socioeconomic Pathways (RFF-SPs) (Rennert et al., 2021). The RFF-SPs project population and GDP as well as global CO_2, CH_4 and N_2O emissions. They address the shortcomings of the original approach to socioeconomic and emissions projections, which were based combinations of the deterministic Shared Socioeconomic Pathway (SSP) narratives as well as the Representative Concentration Pathways (RCPs) (Riahi et al., 2017). The SSPs and RCPs are the result of a scenario development effort that started in the late 2000s to replace the Special Report on Emission Scenarios (SRES) scenarios from the 1990s (EPA, 2022). The two components, SSPs and RCPs, were designed to be complementary. The SSP-RCPs are criticized for failing to enable the quantitative evaluation of uncertainty. The RFF-SPs, on the other hand, explicitly characterize uncertainty in the demographic, economic, and emissions projections. Further, they extend out to 2300 rather than 2100. GIVE extrapolates the SSP-RCPs from 2100 out to 2300.

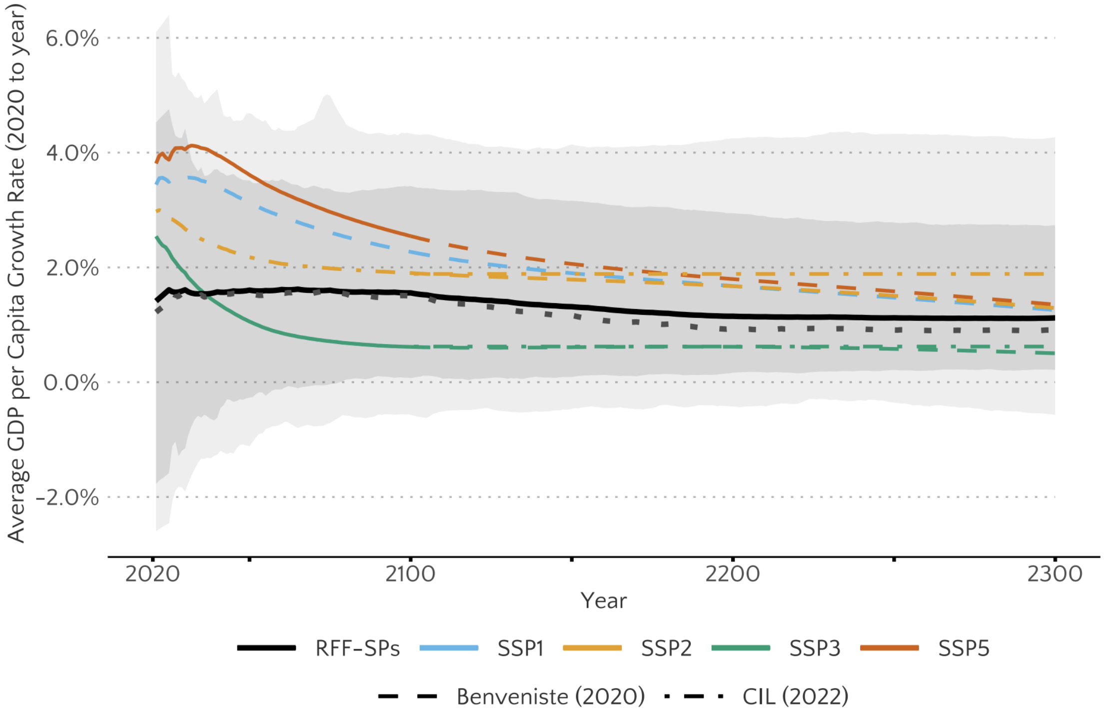
The RFF-SPs were generated based on a combination of statistical and expert-based approaches given the long time horizon relative to the length of the historical record (Rennert et al., 2021; Christensen et al., 2018). Population projections through 2300 were generated by extending the approach used by the United Nations for its official population forecasts to 2100 (Raftery and Ševčíková, 2023). These projections were then altered by incorporating feedback from a panel of nine leading demographic experts. Projections of GDP per capita come from a multifactor Bayesian dynamic model (Müller et al., 2022). Similarly, these projections were then reweighted based on the RFF Economic Growth Survey (Rennert et al., 2021). Finally, the projections of global CO_2, CH_4 and N_2O emissions come from RFF's Future Emissions Survey, which elicited experts' uncertainty ranges for fossil fuel and process-related CO_2 emissions (Rennert et al., 2021). The experts surveyed also quantified the sensitivity of emissions projections to future economic growth, thus allowing for the development of a joint set of projections of emissions and economic growth.

Figure 2 shows the projections of global income growth per capita and CO_2 emissions under the SSP-RCPs and the RFF-SPs. This paper uses the RFF-SPs as the default socioeconomic component and uses the SSP-RCP 1-2.6, 2-4.5, and 3-7.0 for sensitivity analysis.[36] Black lines represent the mean emissions projections and dotted lines represent the median emissions projections. The dark shaded regions show the 5th to 95th percentile ranges while the light shaded regions show the 1st to 99th percentile ranges. Figure 3 maps the same projections for SSP-RCP 1-2.6, 2-4.5, and 3-7.0 in 2100 in order to show the distribution of income and temperature across the globe.

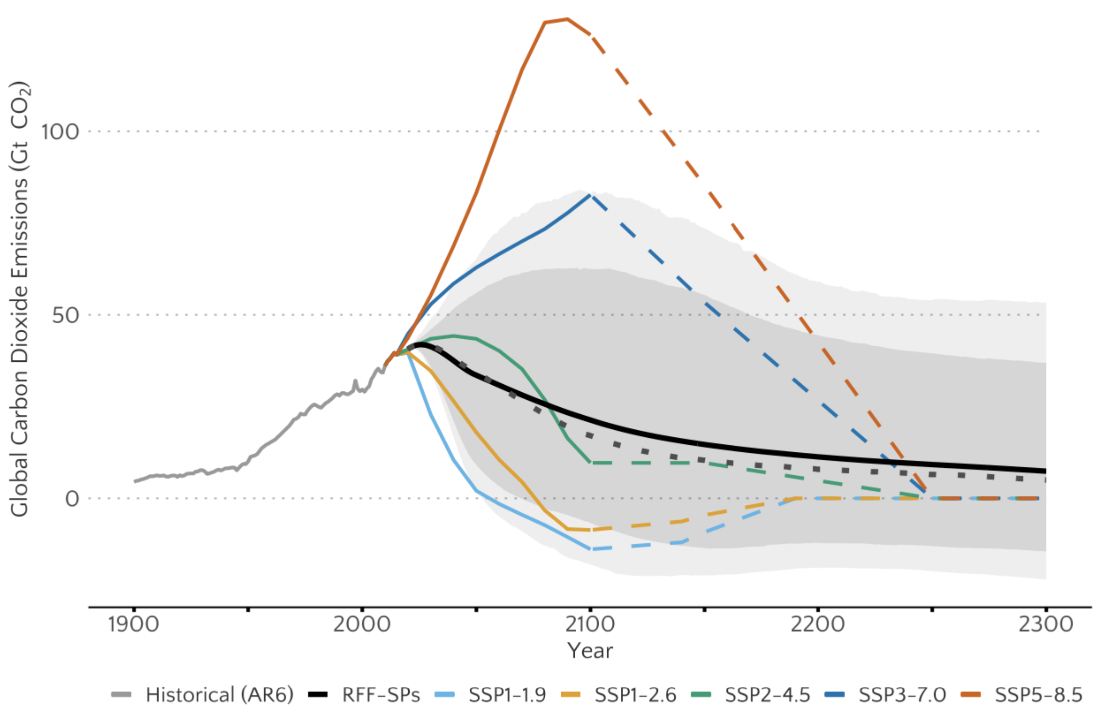
[36] I do not include SSP-RCP 5-8.5 because it is no longer used by the Biden Administration.

Figure 2: Comparing the RFF-SPs to the SSP-RCPs

(a) Growth in global income per capita



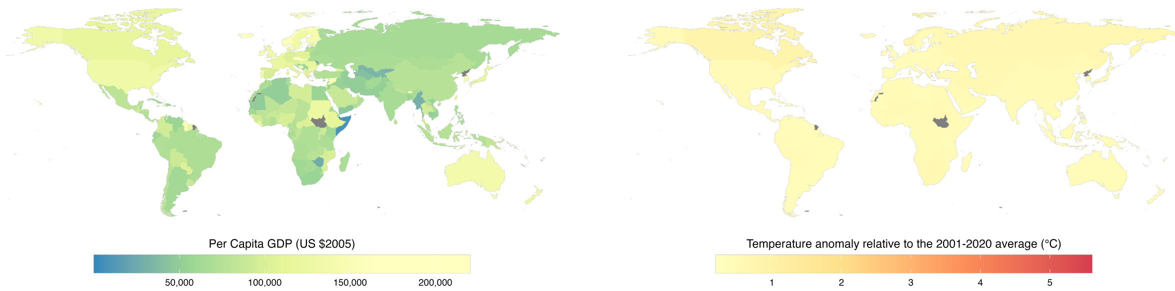
(b) Net annual global emissions of CO_2



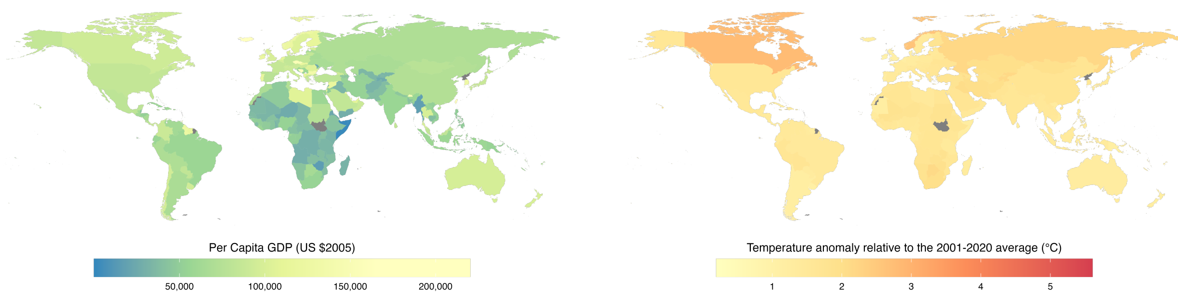
Source: EPA (2022)
Notes: RFF-SP projections based on RFF-SPs (Rennert et al., 2022). Black lines represent the mean (solid) and median (dotted) CO2 emissions projections along with 5th to 95th (dark shade) and 1st to 99th (light shade) percentile ranges. SSP data through 2100 are from the International Institute for Applied Systems Analysis (IIASA) SSP Database (Riahi et al., 2017). SSPs beyond 2100 (dashed lines) are based on the commonly used extensions provided by the Reduced Complexity Model Intercomparison Project (Nicholls et al., 2020).

Figure 3: Distribution per capita GDP and temperature anomaly

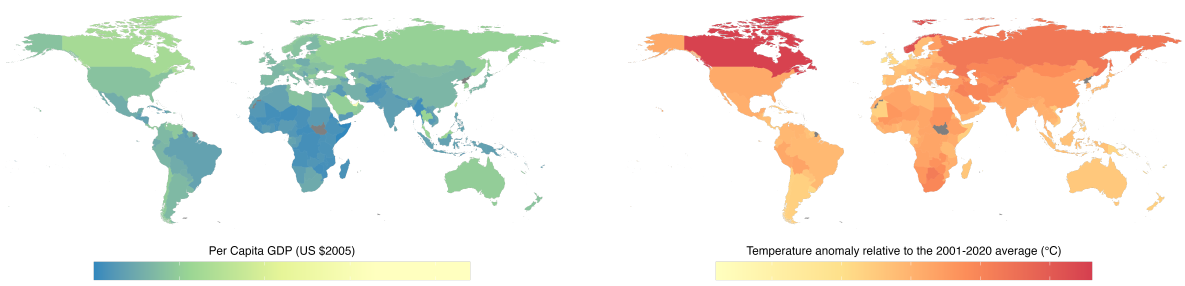
(a) SSP-RCP 1-2.6



(b) SSP-RCP 2-4.5



(c) SSP-RCP 3-7.0



Notes: The map compares projections for 2100 of country-level per capita income (right) and temperature anomaly relative to the 2001-2020 in degrees Celsius (left).

5.1.2 Climate models

FaIR The global climate system is represented by the Finite Amplitude Impulse Response (FaIR) model version 1.6.2 (Smith et al., 2018; Forster et al., 2021). FaIR is an emissions-based climate model with a carbon cycle that depends on background warming levels as well as cumulative carbon uptake by land and ocean sinks. This path-dependent design enables FaIR to replicate the behavior of more sophisticated Earth system models, a feature that was not present in the previous climate models used for SCC calculations.[37] GIVE runs FaIR with randomly sampled CO_2, CH_4, and N_2O emissions time series from the RFF-SPs and represents other greenhouse gases and short-lived climate forcers using the SSP-RCP 2-4.5 scenario.

BRICK Regional changes in sea level are represented using the Building blocks for Relevant Ice and Climate Knowledge (BRICK) model (Wong et al., 2017). BRICK estimates the change in global sea level associated with global mean surface temperature and downscales its global estimates to regional changes using time-invariant scaling factors. There are several climate components, or "BRICKs", which each contribute to global sea level rise: glaciers and small ice caps, the Greenland ice sheet sheet, the Antarctic ice sheet, and thermal expansion. BRICK is calibrated with a Bayesian framework with an aim to accurately estimate the tails of the distribution of future sea levels.[38]

5.1.3 Damage functions

Agriculture The agricultural damage functions are based on Moore et al. (2017). They estimate damages in two steps. First, they use a meta-analysis to estimate the effects of temperature, rainfall, and CO_2 on crop yields. Second, they use a computable general equilibrium (CGE) model to estimate the welfare consequences of these crop yield shocks

[37]The NASEM report highlighted FaIR as an exemplary model for this reason (NASEM, 2017).

[38]See Rennert et al. (2022) for further details on the calibration of the FaIR and BRICK model in GIVE.

while also accounting for trade patterns and supply and demand adjustments in agricultural markets.[39] Moore et al. (2017) present their results in the form of damage functions relating global mean surface temperature and welfare change. Rennert et al. (2022) incorporate the Moore et al. (2017) damage functions as

$$\text{AgPctCost}_{rt} = \sigma_r \left(\frac{\text{GDPpc}_{rt}}{\text{GDPpc}_{r1990}} \right)^{-\epsilon} f_r(T_t),$$

where AgPctCost_{rt} is the damage in the agricultural sector as a proportion of GDP in one of 16 regions r at time t, σ_r is the share of agriculture in GDP in 1990 in region r, $\epsilon = 0.31$ is the income elasticity of agriculture share in GDP, T_t is global average sufrace temperature increases, and f_r is the piece-wise linear function for region r resulting from the two step process described above.

In order to characterize uncertainty, Moore et al. (2017) perform a sensitivity analysis by perturbing four sets of parameters governing the supply and demand behavior in the CGE model. This ultimately results in three piece-wise linear damage functions corresponding to a low, central, and high damage estimate for each of their 16 regions. Rennert et al. (2022) then incorporate this sensitivity analysis as part of GIVE's Monte Carlo framework by assigning these three damage functions to a triangular distribution with lower bound 0, mode 0.5, and upper bound 1, which correspond to the low, central, and high damage estimates respectively. This uncertainty sampling scheme preserves the covariance between regions resulting from the global trade network.

Building energy expenditures The building energy demand damage function is based on Clarke et al. (2018), a study that uses the Global Change Analysis Model (GCAM) to project how climate change affects building energy demand in 12 regions. The damage functions relate global temperature rise to changes in regional energy expenditures expressed

[39]They use the Global Trade Analysis Project (GTAP), a widely used comparative static general equilibrium model that exhaustively tracks bilateral trade flows between all countries.

expressed as a proportion of that region's GDP. This relationship is approximately linear in temperature. Rennert et al. (2022) then fit a linear function by regressing the net change in energy expenditures as a proportion of GDP on global temperature rise relative to the preindustrial period for each of the 12 GCAM regions. This regression yields a coefficient for each region, β_r^E. Energy damages for each country c in region r are therefore calculated as

$$\text{Change in energy expenditures as proportion of } \text{GDP}_{ct} = \beta_r^E \left(\text{Temperature rise}_t\right). \quad (28)$$

The change in energy expenditure share is multiplied by country-level GDP to generate building energy-related damages in dollars in GIVE. No uncertainty is included in this damage function as Clarke et al. (2018) do not explicitly characterize uncertainty in their paper.

Sea-level rise The sea-level rise damage calculations are based on Diaz (2016), who develops the Coastal Impacts and Adaptation Model (CIAM). CIAM is an optimization model that assesses the costs of various adaptation strategies against the costs of flooding damages and regional changes in sea level. It chooses the least-cost strategy for approximately 12,000 coastal segments s across the globe in the Dynamic Interactive Vulnerability Assessment (DIVA) database (Vafeidis et al., 2008). CIAM's adaptation strategies include inland retreat and protection of coastal communities and infrastructure. Damages are due to inundation of unprotected coastal land, wetland loss, and flooding. The objective of each coastal segment is to minimize the sum of adaptation costs plus damages:

$$\begin{aligned} \min_s \sum_t^T &(\text{RetreatCost}_{st} + \text{ProtectionCost}_{st} \\ &+ \text{InundationCost}_{st} + \text{WetlandCost}_{st} + \text{FloodCost}_{st})\ r_t, \end{aligned} \quad (29)$$

where r_t is some exogenous discount factor. Sea-level rise damages are calculated for 145 of the 184 countries in GIVE. No uncertainty is included in the calculation of sea-level rise damages since CIAM is a deterministic model.

Temperature-related mortality The temperature-related mortality damage functions are based on Cromar et al. (2022), a meta-analysis studying the impacts of temperature on all-cause mortality risk, including cardiovascular, respiratory, and infectious disease categories. Cromar et al. (2022) produce disaggregated estimates of the effects on each degree of warming on mortality, β_r^M, for nine regions. Temperature-related mortality is represented using a simple linear model:

$$Y_{ct} = \beta_r^M \text{ (Temperature rise}_t) + \epsilon_{ct}, \tag{30}$$

where Y_{ct} is the percentage increase in the baseline mortality rate of a country c at time t. In order to represent uncertainty, β_r^M is sampled from a normal distribution centered on the point estimate and standard deviation equal to the reported standard error. The percentage increase in the mortality rate is converted into net additional deaths:

$$\text{Excess deaths}_{ct} = (\text{Population}_{ct}) \text{ (Baseline mortality rate}_{ct}) \left(\frac{Y_{ct}}{100}\right) \tag{31}$$

where baseline mortality is defined as the country population level times its baseline mortality rate from the RFF-SPs. Excess deaths are then monetized using the VSL. The GIVE model uses an income-elastic VSL as the default specification:

$$\text{Monetized excess mortality}_{ct} = \text{VSL}_{ct} \text{ (Temperature-induced excess deaths}_{ct}) \tag{32}$$

where VSL is calculated using the benefits transfer methodology as in equation 21.

5.1.4 Discounting

The baseline specification of GIVE evaluates a stochastic discount factor, where $t = 1$ corresponds to the year 2020.

$$r_t = \left(\frac{c_t}{c_1}\right)^{-\eta} \frac{1}{(1+\rho)^t}. \tag{33}$$

The η and ρ values used in GIVE are empirically calibrated to be consistent with the RFF-SPs and evidence on the observed behavior of interest rates (Newell et al., 2022). This approach also produces near-term risk free discount rates (Rennert et al., 2022). The central discount rate used in this paper corresponds to a near-term 2% rate consistent with real risk-free interest rates over the last 30 years as well as the EPA's approach (EPA, 2022). A 2% rate corresponds to (ρ, η) values of (0.2%, 1.24). I also use the same alternative rates as the EPA: a 1.5% rate corresponds to (0.01%, 1.02) while a 2.5% rate corresponds to (0.5%, 1.42).

Note that this is a more specific version of equation 6, since Rennert et al. (2022) defines c_t as global average per capita consumption at time t, rather than the more general c_{xt}, where x can be any reference region. This modeling choice follows directly from NASEM (2017), which states:

> Using region-specific discount rates requires values of ρ and η for each region, as well as a distribution over the rate of growth of per capita consumption in each region. Treating future generations differently based on where they live whether due to differing values of ρ and η or to differing growth rates suggests a need to treat current generations differently on the basis of where they live. This raises the issue of how such regional weights would be determined. The current approach avoids this issue and, by applying the same discount rate to all countries, is in the spirit of OMB guidance, which calls for treating equally persons of different income levels at a given time, for the purposes of valuation.

Indeed, the approach taken by GIVE—and by extension the EPA in the updated SCC—follows the logic of the status quo approach in the discounting module despite attempting to adhering to the pure Kaldor-Hicks approach. Regardless of one's normative stance on the appropriate approach to benefit-cost analysis, all analysts would likely agree that the approach should be consistent throughout the model.

5.2 Modifications and additions to GIVE

5.2.1 The Bressler et al. (2021) temperature-related mortality damage function

Accurate estimates of country-level mortality risk are imperative given this senior essay's focus on the distributional impacts of climate change. I therefore add a new temperature-related mortality damage function to GIVE based on Bressler et al. (2021).[40] While the mortality damages from Cromar et al. (2022) are consistent with the literature at the global level, the distribution of mortality impacts counters one of the most consistent findings in the climate mortality literature—that individuals in hotter and lower income places will be more severely impacted than individuals in higher income and cooler places. For example, their estimated mortality rate increases twice as much in the US compared to Latin America per degree Celsius of warming.

Three factors likely contribute to this result. First, Cromar et al. (2022) assume by construction that damage is linear in temperature. This assumption is inconsistent with the majority of the literature that finds the damage function is convex (Carleton et al., 2022; Bressler et al., 2021; Gasparrini et al., 2017; Bressler, 2021). For the same increase in temperature, places with already high temperatures are expected to be harmed more than places with colder climates as they experience exponentially more days that fall in the steep and curved part of the exposure response function. A linear damage function fails to capture this dynamic. Therefore, Cromar et al. (2022) overestimate mortality damages in colder places and underestimate mortality damages in hotter places.

Second, the Cromar et al. (2022) damage function aggregates results from a limited number of studies with extractable linear damage functions. This means that several of their nine regional damage functions are extrapolated based on very small samples that are likely non-representative. For example, Cromar et al. (2022) use only two studies to estimate

[40] Danny Bressler, Lisa Rennels, Frank Errickson, and David Anthoff assisted with the implementation of the Bressler et al. (2021) mortality damage function in GIVE. Bryan Parthum and David Smith wrote the code to downscale temperature to the country-level in GIVE.

the damage function for the Sub-Saharan Africa region: Diboulo et al. (2012) and Azongo et al. (2012). However, Diboulo et al. (2012) only examines one town in Burkina Faso with a population of 90,000 while Azongo et al. (2012) only studies the Kassena-Nankana Districts of Northern Ghana.

Finally, Cromar et al. (2022) do not account for the benefits of adaptation to reduce vulnerability to temperature-related mortality, as in Bressler et al. (2021) and Carleton et al. (2022). As discussed in Auffhammer (2018), this methodology is likely to overestimate mortality damages since it only considers short-run weather-outcome relations. This effect is magnified in high-income regions where adaptation is strongest.

The Bressler et al. (2021) damage function, on the other hand, is far more consistent with the climate-mortality literature. It accounts for the interaction of temperature with income by allowing for different adaptive responses to temperature-related mortality conditional on the projected income levels. For example, individuals make investments to mitigate the negative mortality effect of heat, such as installing air conditioning (Carleton et al., 2022; Barreca et al., 2016). This feature of the damage function enables it to appropriately distinguish between "weather" and "climate"—or as Auffhammer (2018) writes—between "the impacts of weather simulated with versus without an extensive margin adaptation response."

More specifically, the Bressler et al. (2021) mortality damage function is based on projections from Gasparrini et al. (2017), who model the relationship between daily mortality and mean daily temperatures using a nonlinear distributed lag model. This captures both the lagged effects of exposure to cold on mortality as well as the convex relationship between exposure to heat on mortality discussed above. Gasparrini et al. (2017) study 451 locations in 23 countries, which Bressler et al. (2021) then extrapolate to all countries separately for heat- and cold- related mortality. The model for heat-related mortality is

$$\begin{aligned} Y_{ct}^{\text{Heat}} &= \beta_1 T_{ct} + \beta_2 T_{ct}^2 + \beta_3(\text{Hottest Month Avg Temp}_c) \\ &\quad + \beta_4 T_{ct}(\text{Hottest Month Avg Temp}_c)(\log(\text{GDPpc}_{ct})) + \epsilon_{ct}, \end{aligned} \tag{34}$$

where Y^{Heat} is the percentage increase in the mortality rate due to heat in country c at time t, T is the increase in yearly average temperatures relative to the 2001-2020 period, Hottest Month Avg Temp$_c$ is the population-weighted average temperature in the hottest month in country c between 1984 and 2015, and GDPpc$_{ct}$ is per capita GDP.[41] The model for cold-related mortality is

$$Y_{ct}^{\text{Cold}} = \beta_1 T_{ct} + \beta_2 T_{ct}^2 + \beta_3(\text{Coldest Month Avg Temp}_c) + \epsilon_{ct}, \tag{35}$$

which is analogous to the heat model except it does not include the interaction term with income. An alternative specification in Bressler et al. (2021) includes the income interaction term, but it does not perform as well on in-sample and out of sample tests. In order to represent uncertainty, a vector of coefficients for the heat and cold models is sampled from a multivariate normal distribution centered on the point estimate and standard deviation equal to the reported standard error. The net percentage increase in mortality rate, Y_{ct}, is the sum of Y_{ct}^{Heat} and Y_{ct}^{Cold}. After the calculation of Y_{ct}, monetization of premature mortality risk occurs in the same manner as in the Cromar et al. (2022) damage function (see equations 31 and 32).

I make a a few modifications to the damage function as originally published to ensure consistent behavior in tail socioeconomic and emissions scenarios.[42] First, I set the minimum percentage change in a country's baseline mortality rate due to heat to zero. Second, I ensure that the heat model is nondecreasing under higher temperatures and the cold model is nonincreasing under higher temperatures (holding income constant). In order to do so, equations 34 and 35 are implemented as piecewise functions: if the first order conditions

[41] There are seven countries out of the 184 countries in the GIVE model for which population-weighted average temperatures are not available. Population-weighted average temperatures are needed to calculate the hottest and coldest month for each country. I assign these seven countries the values of their neighbor as follows: Aruba is assigned Venezuela, Bahrain is assigned Saudi Arabia, Barbados and St. Lucia are assigned Puerto Rico, the Maldives are assigned Sri Lanka, Malta is assigned Tunisia, Singpore is assigned Malaysia, and Tonga is assinged Fiji.

[42] Danny Bressler and I worked together to implement these modifications.

below are satisfied, the equations as implemented as written; else temperature is held constant at the maximum temperature at which heat (cold) mortality starts decreasing (increasing) with higher temperatures.

$$\frac{\partial Y_{ct}^{\text{Heat}}}{\partial T_{ct}} \geq 0$$

$$\implies \beta_1 T_{ct} + 2\beta_2 T_{ct} + \beta_3(\text{Hottest Month Avg Temp}_c)$$

$$+\beta_4 T_{ct}(\text{Hottest Month Avg Temp}_c)(\log(\text{GDPpc}_{ct})) \geq 0$$

$$\frac{\partial Y_{ct}^{\text{Cold}}}{\partial T_{ct}} \leq 0$$

$$\implies \beta_1 T_{ct} + 2\beta_2 T_{ct} + \beta_3(\text{Coldest Month Avg Temp}_c) \leq 0$$

Figures 4-6 compare the distribution of mortality impacts in the Bressler et al. (2021) damage function with the Cromar et al. (2022) damage function under the three deterministic socioeconomic and emissions trajectories in 2100. Each of these figures can be compared with Figure 3, which shows the distribution of income and temperature in 2100.

Figure 4 shows results under SSP-RCP 1-2.6, a low emissions, moderate income scenario. The Bressler et al. (2021) damage function estimates less mortality risk than the Cromar et al. (2022) damage function in high income countries such as the US or Australia since they benefit from a reduction in cold-related mortality and the use of income to offset some of the effects of heat-related mortality.

Figure 5 shows mortality impacts SSP-RCP 2-4.5, a moderate emissions, moderate income scenario. I focus primarily on this scenario given it most closely approximates the RFF-SPs. Under this scenario, the Bressler et al. (2021) damage function is consistent with the finding that hotter and lower income places will be most severely impacted from climate change. For example, in Somalia, climate change is predicted to increase the baseline mortality rate by

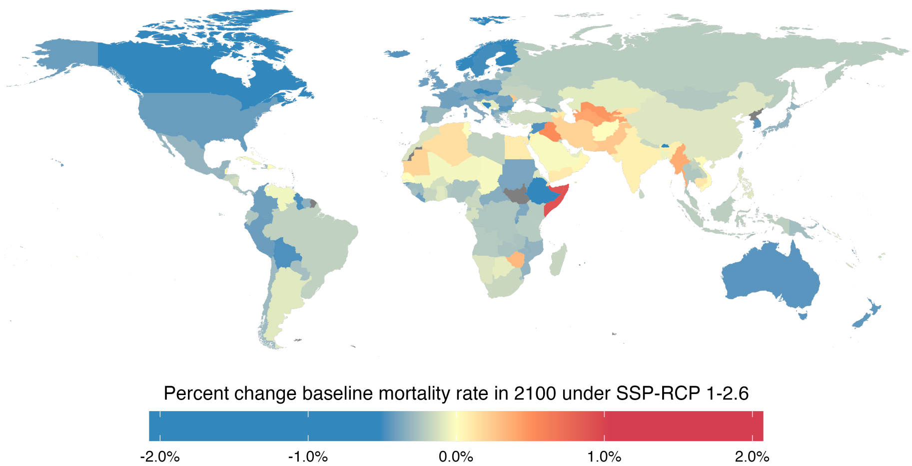
5.1%, corresponding to an additional 540 deaths per 100,000 individuals under SSP-RCP 2-4.5 in 2100. On the other hand, the Cromar et al. (2022) mortality damage function predicts that climate change will only increase the baseline mortality rate by 0.007% in Somalia under the same scenario, approximately half the predicted increase in the US (0.013%). Further, the figure shows how the Bressler et al. (2021) allows for gains in many regions in the global north due to the reduction in the number of deadly cold days as well as the benefits of income growth, consistent with Carleton et al. (2022). For example, in Germany, climate change is predicted to decrease the baseline mortality rate by 0.8%, saving approximately 7 lives per 100,000 individuals.

Figure 6 shows results under SSP-RCP 3-7.0, a moderate emissions, moderate income scenario. Consistent with the climate mortality literature, the Bressler et al. (2021) damage function estimates far greater mortality risk in Sub-Saharan Africa and South Asia, compared to the Cromar et al. (2022) damage function, which estimates greater mortality risk in the US than in South America and Sub-Saharan Africa.

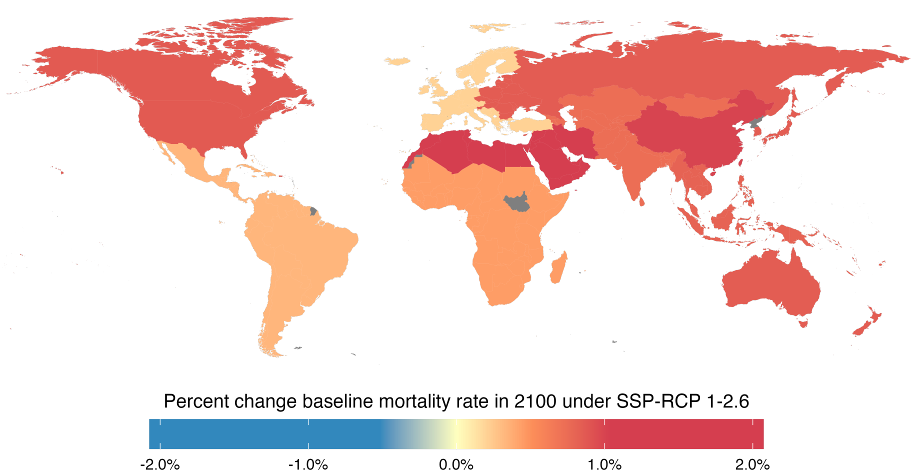
Overall, each of these figures emphasize the significantly different distribution of damages under the Cromar et al. (2022) and Bressler et al. (2021) damage functions. Clearly, the mortality partial SCCs under each damage function will diverge when the distribution of damages is accounted for.

Figure 4: The distribution of the mortality impacts of climate change differs by damage function (SSP-RCP 1-2.6)

(a) Bressler et al. (2021)



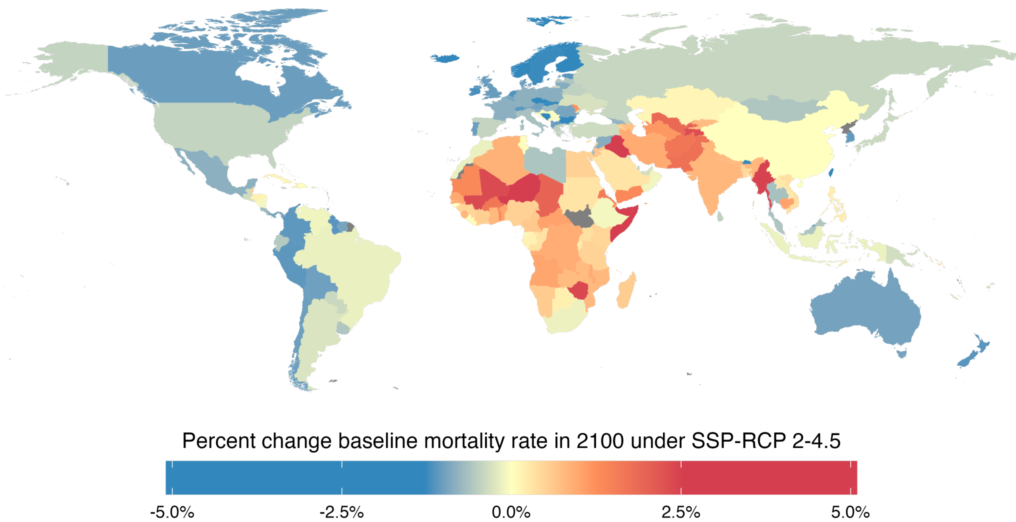
(b) Cromar et al. (2022)



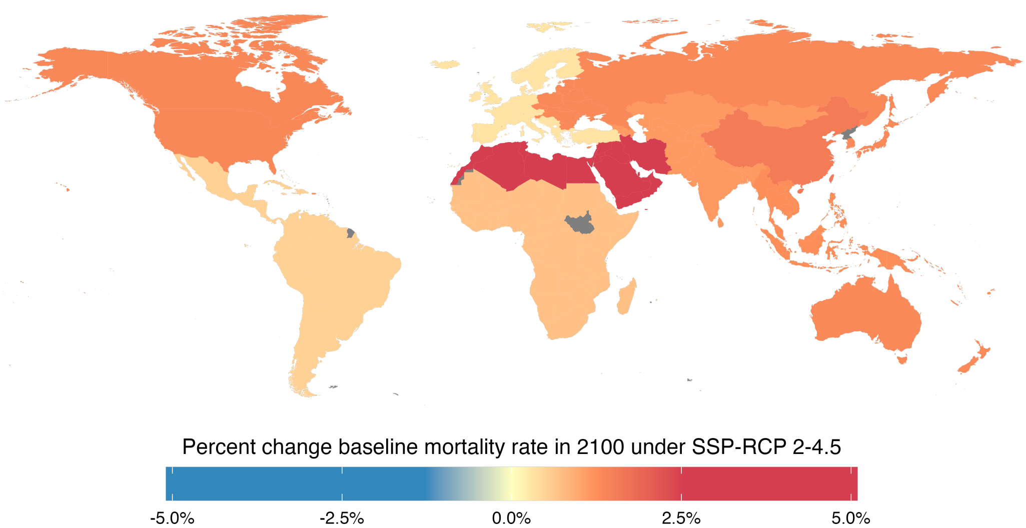
Notes: The map compares estimates of the percent increase in mortality risk due to climate change in the Cromar et al. (2022) damage function and the Bressler et al. (2021) damage function. All values shown refer to the SSP-RCP 1-2.6 emissions/socioeconomic scenario.

Figure 5: The distribution of the mortality impacts of climate change differs by damage function (SSP-RCP 2-4.5)

(a) Bressler et al. (2021)



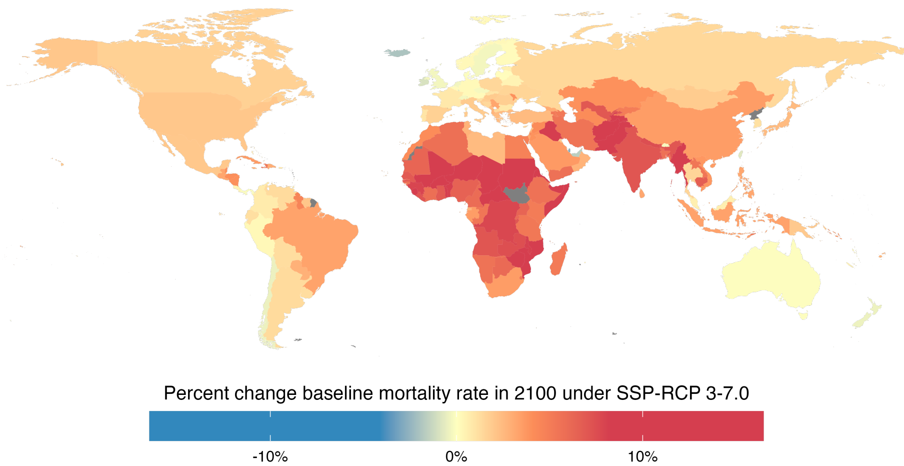
(b) Cromar et al. (2022)



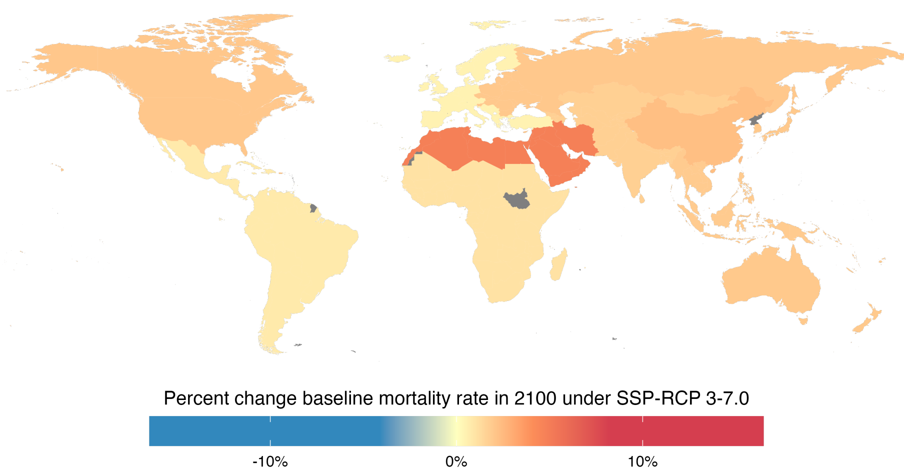
Notes: The map compares estimates of the percent increase in mortality risk due to climate change in the Cromar et al. (2022) damage function and the Bressler et al. (2021) damage function. All values shown refer to the SSP-RCP 2-4.5 deterministic emissions/socioeconomic scenario, which is most directly comparable to the RFF-SPs.

Figure 6: The distribution of the mortality impacts of climate change differs by damage function (SSP-RCP 3-7.0)

(a) Bressler et al. (2021)



(b) Cromar et al. (2022)



Notes: The map compares estimates of the percent increase in mortality risk due to climate change in the Cromar et al. (2022) damage function and the Bressler et al. (2021) damage function. All values shown refer to the SSP-RCP 3-7.0 emissions/socioeconomic scenario.

5.2.2 VSL flexibility

In order to implement each of the three approaches to benefit-cost analysis, I add additional flexibility to GIVE to allow for the calculation of monetized excess mortality with a global average VSL:

$$\text{Monetized excess mortality}_{ct} = \text{VSL}_{xt}\ (\text{Temperature-induced excess deaths}_{ct}), \tag{36}$$

where VSL_{xt} is calculated with the reference region x as the globe at time t. This enables the confirmation of the theoretical result of the equivalence between the partial mortality SCC under the status quo and equity weighted approaches with the globe as the reference region and $\eta = \epsilon$.

5.2.3 Equity weighting and discounting

I implement equity weighting in a two-step process in the discounting module.[43] First, country-level marginal damages in the energy, sea-level rise, and mortality sectors are converted to utils based on income at the country level. Marginal damages in the agricultural sector at the regional level are converted to utils based on income at the regional level. Damages in each sector in utils are summed to yield total damage in utils and discounted with ρ. Second, total damages in utils are multiplied by the reference region's income in utils to yeild the equity weighted SCC.

$$1.\ \text{Total damages in utils} = \sum_{t=1}^{T}\sum_{r=1}^{R} D_{rt}\left(\frac{1}{\bar{c}_{rt}}\right)^{\eta}\frac{1}{(1+\rho)^t}$$

$$2.\ \text{SCC}'_{\text{EW}} = \sum_{t=1}^{T}(\text{Total damages in utils})\ (\bar{c}_{xt})^{\eta}$$

I implement equity weighting with c defined as income rather than consumption (income

[43] I use code provided by Lisa Rennels and David Anthoff as a baseline for my implementation of equity weighting. I modify it in two ways: (1) to include the Bressler et al. (2021) damage function, and (2) to add the option to use the globe as a reference region.

net of climate damages) for consistency with the benefits-transfer approach in GIVE which extrapolates VSL based on the income of other countries. Further, since I define c as income for equity weighting and calculating the VSL, I also define c as income for Ramsey discounting in non-equity weighted specifications. This means that even my specification of GIVE with the Cromar et al. (2022) mortality damage function does not exactly match that in Rennert et al. (2022).

The first-best approach would use consumption for equity weighting, discounting, *and* in the calculation of VSL; however, consumption at the country-level is not currently available in GIVE because damages in the agricultural sector are only available at the regional level. This limitation is technical rather than conceptual. It may be possible to downscale agricultural damages to the country-level with careful treatment of the inter-regional interactions (e.g., trade) in the Moore et al. (2017) damage function.

This discussion points to a larger issue in GIVE: consistency in the definition of c. Future versions of GIVE should consistently apply consumption across the model. If it is not possible to downscale consumption to the country level, then future versions of GIVE should consistently apply income across the model as I do in this senior essay. Failure to do so may lead to dismal theorem-like results in very high emissions scenarios (Weitzman, 2009). For example, in the mortality sector, the discount factor will approach infinity but willingness to pay to avoid mortality risk will not approach 0 if VSL is not calculated with consumption.[44]

5.3 Estimating the SCC

I estimate the SCC under each approach in a three step process. First, I run the GIVE model out to 2300 for two cases: a baseline case and a perturbed case that adds an extra 0.1Mt pulse of CO_2 emissions in the year 2020. Second, I numerically estimate the marginal damages $\tilde{D}_{rt}$

[44] I thank Danny Bressler for observing this point.

in year t and region r as the difference in damages between the pulse and baseline runs:

$$\tilde{D}_{rt} = \sum_{d=1}^{4} \text{Damages with pulse}_{rt} - \text{Baseline damages}_{rt}, \tag{37}$$

where damages are aggregated across each of the four damage sectors d at their respective geographic resolutions r (that is, regions or countries). Important to note is that $\tilde{D}_{rt}$ is a partial estimate of marginal damages. GIVE does not yet accommodate the estimation of other categories of temperature driven climate impacts (e.g., storm damage, morbidity, conflict, migration, biodiversity loss), damages that result from physical impacts other than temperature and sea-level rise (e.g., changes in precipitation, ocean acidification), or many feedbacks and interactions across sectors and regions that can lead to additional damages (EPA, 2022).

Third, the SCC under each approach is calculated by equity weighting (if applicable), aggregating over each region r, and discounting marginal damages:

$$\widetilde{\text{SCC}}'_{\text{KH}} = \sum_{r=1}^{R} \sum_{t=1}^{T} \tilde{D}_{rt} r_t \tag{38}$$

$$\widetilde{\text{SCC}}'_{\text{EW}} = \sum_{r=1}^{R} \sum_{t=1}^{T} \left(\frac{\bar{c}_{x1}}{\bar{c}_{rt}} \right)^{\eta} \tilde{D}_{rt} \frac{1}{(1+\rho)^t} \tag{39}$$

$$\widetilde{\text{SCC}}'_{\text{SQ}} = \sum_{r=1}^{R} \sum_{t=1}^{T} \tilde{D}^{\text{NM}}_{ct} r_t + \left(\frac{\bar{c}_{x1}}{\bar{c}_{rt}} \right)^{\eta} \tilde{D}^{\text{M}}_{rt} \frac{1}{(1+\rho)^t}, \tag{40}$$

These equations are equivalent to equations 25 - 27 with the exception that D_{rt} is now approximated by $\tilde{D}_{rt}$. In addition, as discussed in Section 3, the baseline specification of GIVE is not equivalent to the Kaldor-Hicks SCC since income is measured in PPP-adjusted dollars.

I show the distribution of 10,000 SCC estimates and summarize the distribution by its mean $\mathbb{E}[\text{SCC}]$, where the expectation operator is taken jointly over all uncertain parameters determining marginal damages ($\tilde{D}_{rt}$) and the discount factor (either r_t or $1/(1+\rho)^t$). This methodology partially accounts for the risk premium in the valuation of marginal CO_2 emissions due to the many compounding uncertainties in the model (Rennert et al., 2022).[45]

6 Results

In the following section, I compute the SCC under three specifications. Results calculated with a country-level VSL are consistent with EPA's methodology in the updated SCC. This approach is consistent with pure Kaldor-Hicks approach in that it approximates willingness to pay, but importantly differs from it because GIVE uses PPP-adjusted dollars. Results calculated with a global average VSL are consistent with a global extension of the domestic status quo approach. Equity weighted results are consistent with the equity weighted approach. My preferred specification uses a global average VSL, the Bressler et al. (2021) mortality damage function, and a 2% near-term discount rate. All results are shown in 2020 US$.

Table 2 shows the evolution of the SCC from the base DICE-2016R deterministic model with a 3% discount rate to my preferred specification. The largest contributor to the overall increase in the SCC relative to the DICE model is the use of a global average VSL rather than a country-level VSL. The second largest contributor is the use of a lower near-term discount rate.

I start by running DICE-2016R which yields a mean SCC of $44. This value is comparable to the most commonly cited $51 estimated by the Obama administration 2017 and used by the Biden administration for its interim update (The White House, 2017). Updating the climate modeling, socioeconomic scenarios, and the discounting approach to reflect a 3% near-term discount rate increases the SCC to $59. Replacing the DICE-2016R damage function with the baseline GIVE model's sectoral damage functions increases the SCC to $80. Reducing the near-term discount rate to 2% increases the SCC to $185. This estimate matches the preferred specification in Rennert et al. (2022).

[45]Note that GIVE does not address the equity premium puzzle. This issue outside the scope of this paper.

Table 2: Evolution of mean SCC from DICE-2016R to this study

	Model	Specification	Mean SCC	Incremental change (\$ per tCO_2)	Share of total change to **preferred** (%)
1	DICE-2016R	3% near-term discount rate Consumption discounting	44		
2	GIVE DICE damage function	3% near-term discount rate Consumption discounting	59	15	4
3	GIVE Cromar et al. (2022)	Country-level VSL 3% near-term discount rate Consumption discounting	80	21	6
4	GIVE Cromar et al. (2022)	Country-level VSL 2% near-term discount rate Consumption discounting	185	105	31
5	GIVE Cromar et al. (2022)	Country-level VSL 2% near-term discount rate Income discounting	180	-5	-1
6	GIVE Bressler et al. (2021)	Country-level VSL 2% near-term discount rate Income discounting	231	51	15
7	GIVE Bressler et al. (2021) **(preferred)**	Global average VSL 2% near-term discount rate Income discounting	380	149	44
8	GIVE Bressler et al. (2021)	Equity weighting 2% near-term discount rate Income discounting	504	124	

Notes: All SCC values are expressed in 2020 US dollars per metric ton of CO_2 and represent the mean value from 10,000 Monte Carlo simulations. Row 1 shows the mean SCC of \$44 estimated using the DICE 2016R deterministic model. This value is comparable to the value previously estimated by IWG DICE-2010 of \$46 as well as the most commonly cited \$51, estimated by the IWG in 2017 and used by the Biden administration for its interim update (The White House, 2017). Row 2 then retains the DICE-2016R damage function but otherwise uses GIVE under discounting parameters of ρ=0.8%, η=1.57, which are consistent with a 3% near-term discount rate. Row 3 replaces the DICE-2016R damage function with the sectoral damage functions from Rennert et al. (2022), including the temperature-related mortality function from Cromar et al. (2022). Row 4 and all following rows use the IWG's current preferred discounting parameters of ρ=0.2%, η= 1.24, which are consistent with a 2% near-term discount rate. Row 5 switches to discounting based on income rather than consumption in order to be consistent with equity weighting based on income in a subsequent specification. Row 6 replaces the Cromar et al. (2022) temperature-related mortality function with the Bressler et al. (2021) temperature-related mortality. Row 7 then uses a global average VSL rather than a country-level VSL, the preferred mean value from this study. Row 8 implements equity weighting. Table inspired by Rennert et al. (2022), table 2.

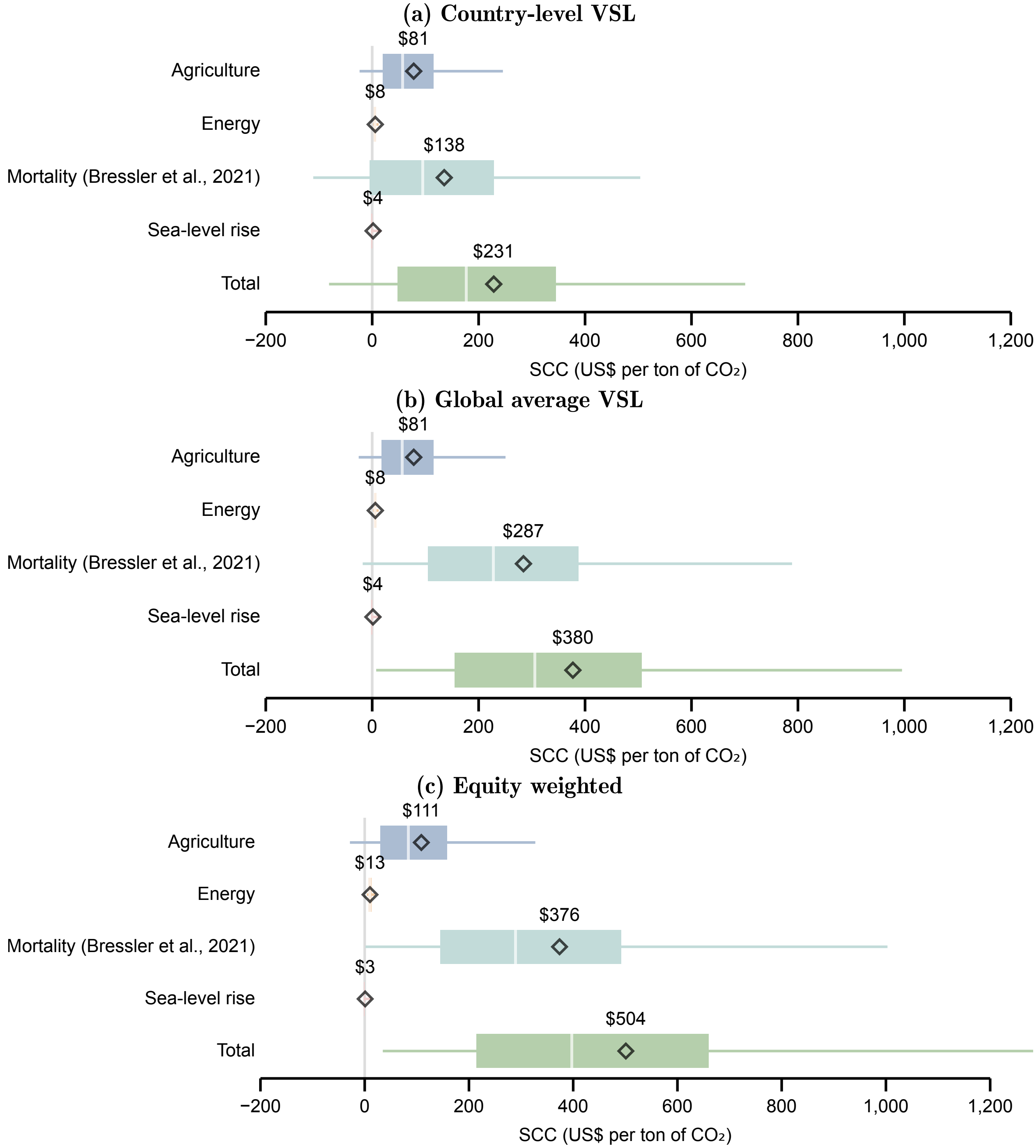
Next, switching from discounting based on consumption to discounting based on income reduces the SCC by $5. As discussed in Section 5, this is not the first-best method, but necessary for consistency with the VSL calculation given the current constraints of the GIVE model. Replacing the Cromar et al. (2022) mortality damage function with the Bressler et al. (2021) mortality damage function increases the SCC further to $231. Finally, using a global average VSL increases the SCC to $380 while equity weighting with the globe as the reference region increases the SCC to $504.

Figure 7 disaggregates estimates of the SCC under each of the three monetization approaches into partial SCC estimates by sector. The four damage sectors vary substantially in their respective contributions to the magnitude and uncertainty of the SCC. Figure 7a shows results using a country-level VSL. Temperature mortality impacts are the largest driver of the SCC, contributing a mean partial SCC of $138 to the $231 total. Temperature mortality impacts also have the largest uncertainty, with a 5%-95% partial SCC range spanning $-108 to $506. This large range arises due to the compounding uncertainty in the relationship between income and temperature-related mortality. Temperature mortality impacts under the Cromar et al. (2022) mortality damage function are far less uncertain. The 5%-95% partial SCC range spans from $-34 to $156. Agricultural impacts are the second-largest contributor to the total SCC as well as to uncertainty due to the relationship between CO_2, temperature and crop yields, and the effect on human welfare (Moore et al., 2017). The relatively small contribution of sea-level rise is attributable to the impact of sea-level inertia and the optimal regional adaptation response in the CIAM model while the small contribution of energy costs is attributable to decreased heating demand and future technological progress offsetting of increased energy demand from cooling (Rennert et al., 2022).

Moving from a country-level VSL to global average VSL (Figure 7b) only affects the mortality partial SCC, which increases from $138 to $287. This increase is attributable to the distribution of mortality impacts in the Bressler et al. (2021) mortality damage function. Using a global average VSL up weights the larger mortality impacts in low-income countries.

Finally, moving from a global average VSL to equity weighting (Figure 7c) increases the partial SCC in all sectors. The agriculture partial SCC increases from \$81 to \$111, the energy partial SCC increases from \$8 to \$13, and the sea-level rise partial SCC decreases from \$4 to \$3, though this small change is likely attributable to randomness from the Monte Carlo simulations. The mortality partial SCC increases to \$376, a 31% increase relative to using a global average VSL. This increase results from the income elasticity of marginal utility exceeding the VSL elasticity ($\eta = 1.24 > \epsilon = 1$) under a 2% near-term discount rate. Overall, the equity weighted SCC is approximately twice as large as the SCC calculated with a country-level VSL.

Figure 7: Estimates of the partial SCC estimates by sector and specification



Notes: Figure shows box and whisker plots of partial SCC estimates in each sector with a 2% near-term discount rate for the three approaches to monetization. The figure depicts the median (center white line), 25%–75% quantile range (box width), and 5%–95% quantile range (colored horizontal lines) partial SCC values. Black diamonds highlight each sector's mean partial SCC, with the numeric value written directly above. All SCC values are expressed in 2020 US dollars per metric ton of CO_2. Subfigure (a) shows estimates using a country-level VSL, subfigure (b) shows how the mortality partial SCC changes using a global average VSL, and subfigure (c) shows all how partial SCCs change with equity weighting. Figure code adapted from Rennert et al. (2022).

6.1 Estimates of the mortality partial SCC

Table 3 reports mortality partial SCC estimates to highlight the impact of the three monetization approaches. The columns apply the three annual discount rates used by the EPA in the updated SCC (EPA, 2022). Standard errors reflect uncertainty in the socioeconomic pathway, climate sensitivity, and in the damage function for the mean SCC estimate. All values represent the discounted global sum of each countries' mortality damages from the release of an additional metric ton of CO_2 in 2020.

Panel A reports estimates of the mortality partial SCC with the main specification of the Bressler et al. (2021) mortality damage function. Under a 2% discount rate, the mortality partial SCC increases from \$138 to \$287 to \$376 when moving from a country-level VSL to global average VSL to equity weighting. The key role of the discount rate in determining the mortality partial SCC is evident when comparing estimates across columns. When using a global average VSL (row 2), the mortality partial SCC varies from \$400 using a 1.5% discount rate to \$203 using a 2.5% discount rate. See Appendix Figure A.1 for the distribution of SCC estimates using a 3.0% and 5.0% discount rate.

Panel B reports estimates of the mortality partial SCC using an alternative specification of the Bressler et al. (2021) mortality damage function which holds income fixed at its 2020 value. Using $r = 2.0\%$ and a global average VSL, the mortality partial SCC is 2.2 times greater when holding income fixed at its 2020 value. Note that this approach is roughly comparable to that of Cromar et al. (2022) (Panel C), which does account for the effect of income growth whatsoever. However, the estimates of the mortality partial SCC using the Cromar et al. (2022) mortality damage function are significantly lower than both of the Bressler et al. (2021) damage function specifications. The linear shape of the Cromar et al. (2022) damage function causes it to underestimate damages in high emissions scenarios relative to a convex damage function.

Figure 8 shows the distribution of 10,000 mortality partial SCC estimates for the main specifications of both damage functions. Dashed vertical lines highlight the mean SCC values

Table 3: Estimates of the mortality partial SCC vary by monetization approach and damage function

	Near-term discount rate		
	$r = 1.5\%$ (1)	$r = 2\%$ (2)	$r = 2.5\%$ (3)
Panel A: Bressler et al. (2021)			
With income protection from heat vulnerability			
RFF-SPs, Country-level VSL	171.8	137.9	102.5
	(3.5)	(2.1)	(1.5)
RFF-SPs, Global average VSL	399.8	286.7	203
	(4.2)	(2.8)	(1.9)
RFF-SPs, Equity weighted	429.2	376.3	320
	(23.4)	(6.6)	(3.3)
Panel B: Bressler et al. (2021)			
Without income protection from heat vulnerability			
RFF-SPs, Country-level VSL	850.8	461.8	272.6
	(4.6)	(2.6)	(1.6)
RFF-SPs, Global average VSL	1117.8	616.9	371.7
	(5.8)	(3.4)	(2.2)
RFF-SPs, Equity weighted	1134.2	741	525.4
	(6.1)	(4.2)	(3.2)
Panel C: Cromar et al. (2022)			
RFF-SPs, Country-level VSL	150.6	87.2	55.3
	(0.6)	(0.4)	(0.3)
RFF-SPs, Global average VSL	133.4	77.2	48.9
	(0.6)	(0.4)	(0.2)
RFF-SPs, Equity weighted	133.3	83.8	58.1
	(1.7)	(0.6)	(0.3)

Notes: All mortality partial SCC values are expressed in 2020 US dollars per metric ton of CO2 and represent the mean value from 10,000 Monte Carlo simulations. Parentheses show the uncertainty standard error. An income elasticity of 1 is used to scale the US EPA VSL value when using country-level VSLs or equity weighting. Panel A shows estimates under the main specification in this paper, the Bressler et al. (2021) damage function with income protection from heat vulnerability. Panel B shows the Bressler et al. (2021) damage function without income protection from heat vulnerability in order to compare with the Cromar et al. (2022) damage function. Panel C shows the Cromar et al. (2022). All estimates use the RFF-SPs for socioeconomic and emissions projections.

while the box and whisker plots at the bottom of the figure show the SCC distribution for each specification. The figure emphasizes the difference in uncertainty between the two damage functions resulting from the Bressler et al. (2021) damage function's inclusion of income and convex structure.

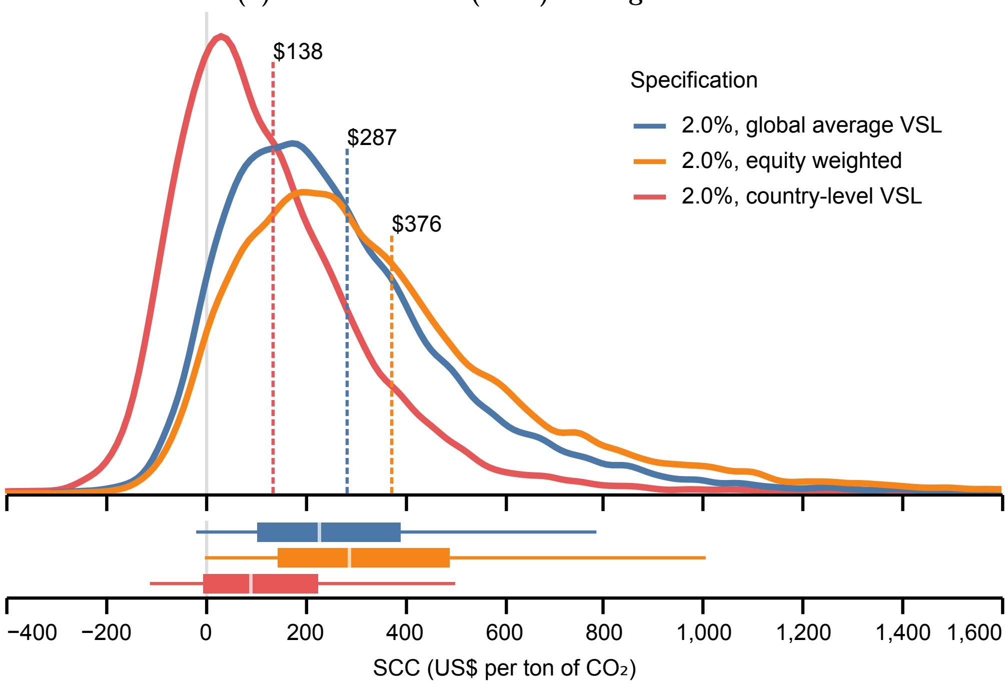
Some features of these results are worth noting. First, estimates of the mortality partial SCC using a global average VSL approach equity weighting estimates as η approaches 1. When $\eta = \epsilon = 1$, the mortality partial SCCs are exactly equivalent when run under deterministic socioeconomic and emissions pathways, confirming the theoretical result proved in Section 4. Under the Bressler et al. (2021) damage function and $\rho = 0.2\%$, the mortality partial SCC using a global average VSL *and* when equity weighted is \$-50 under SSP-RCP 1-2.6, \$11 under SSP-RCP 2-4.5, and \$522 under SSP-RCP 3-7.0. The two values diverge slightly when randomness is introduced in the Monte Carlo simulations. Under the same specification but now using the RFF-SPs, the mortality partial SCC is \$412 using a global average VSL and \$403 when equity weighted.

Second, the mortality partial SCC estimates are less sensitive to the discount rate under the Bressler et al. (2021) damage function than under the Cromar et al. (2022) damage function. When using a global average VSL, moving from a 1.5% discount rate to a 2.5% discount rate decreases the mortality partial SCC by 49% under the Bressler et al. (2021) damage function and by 63% under the Cromar et al. (2022) damage function. The Cromar et al. (2022) damage function predicts greater damages in the distant future while the Bressler et al. (2021) mortality damage function allows income growth to offset a portion of future damages.

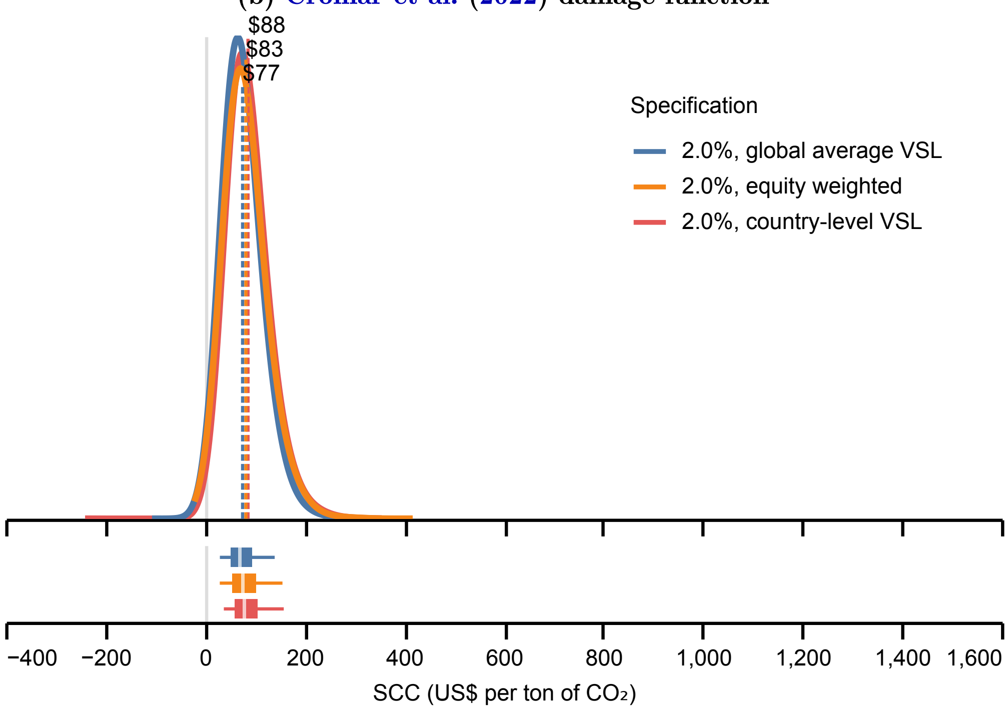
Third and perhaps most importantly, the mortality partial SCC increases when moving from a country-level VSL to a global average VSL and equity weighting under both Bressler et al. (2021) specifications, but decreases under the Cromar et al. (2022) specification. Under the preferred Bressler et al. (2021) specification, moving from a country-level VSL to a global average VSL increases the mean mortality partial SCC by a factor of 2.1. This increase is

Figure 8: The distribution of mortality partial SCC estimates varies by monetization approach and damage function

(a) Bressler et al. (2021) damage function



(b) Cromar et al. (2022) damage function



Notes: Figure shows distributions of the mortality partial SCC under a country-level VSL, global average VSL, and equity weighting. The reference region is the globe under the equity weighted specification. The discount rate is held constant at 2%. Box and whisker plots along the bottom of the figure show the median of each SCC distribution (center white line), 25%–75% quantile range (box width), and 5%–95% quantile range (colored horizontal lines) values. All SCC values are expressed in 2020 US dollars per metric ton of CO2. Figure code adapted from Rennert et al. (2022).

consistent with Carleton et al. (2022), whose mean mortality partial SCC increases by a factor of 3.1 when moving from a regionally-varying VSL to a global average VSL under SSP-RCP 3-4.5. Under Cromar et al. (2022), however, the mortality partial SCC decreases by a factor of 0.12. This is because the Cromar et al. (2022) damage function estimates less mortality damages in lower income, hotter regions (e.g., Central and South America, Sub-Saharan Africa) than in higher income, cooler regions (e.g., North America, Asia). Using a global average VSL decreases the VSL in these high-income regions and therefore decreases the mortality partial SCC. Under the Cromar et al. (2022) damage function, the equity weighted mortality partial SCC is greater than the mortality partial SCC estimated using a global average VSL because $\eta > \epsilon$, but still lower than the mortality partial SCC estimating using a country-level VSL.

Finally, the mortality partial SCC estimates vary by socioeconomic and emissions scenario in addition to mortality damage function. Appendix Tables A.1-A.3 report alternative estimates based on 10,000 Monte Carlo simulations of the SSP-RCPs under each of the monetization approaches. The SSP-RCPs were originally designed to be run deterministically, but GIVE allows one to run them with Monte Carlo simulations as well. Estimates under the Bressler et al. (2021) mortality damage function are more sensitive to changes in the socioeconomic and emissions scenario for two reasons. First, income directly influences damages in the Bressler et al. (2021) mortality damage function. Second, the convex shape of the Bressler (2021) mortality damage function results in higher damage estimates for high emissions scenarios. Regardless, the important result that moving from a country-level VSL to a global average VSL has opposite effects under the two damage functions is robust to each socioeconomic and emissions scenario.

6.2 Equity weighting

There are three important choices that affect the equity weighted results: one empirical and two ethical. The empirical choice is which mortality damage function to use. By accounting for diminishing marginal utility of income, equity weighting up weights the value of avoided mortality risk for individuals in low-income countries. By virtue of estimating greater mortality damages in low-income countries, the Bressler et al. (2021) damage function yields a larger mortality partial SCC and therefore a larger SCC. On the other hand, the Cromar et al. (2022) mortality damage function yields a smaller mortality partial SCC using equity weighting instead of a country-level VSL. The equity weighted SCC under the Cromar et al. (2022) damage function is still larger when aggregating across all damage sectors, but only because the increases in the agricultural and energy mortality partial SCCs are greater than the decrease in the mortality partial SCC.

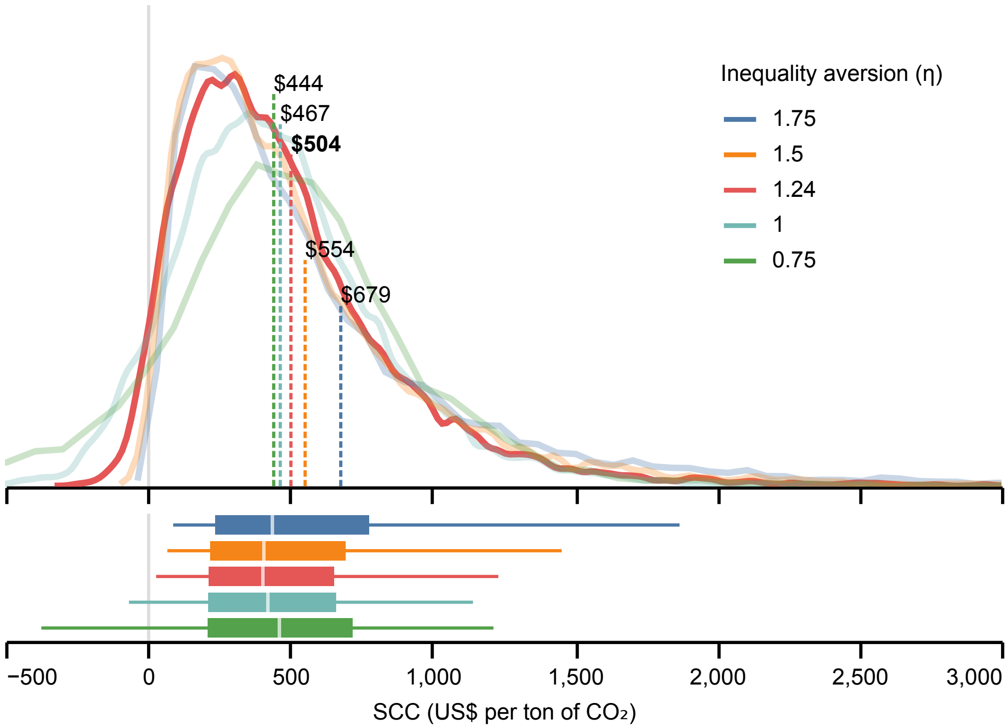
Figure 9 shows the importance of the second choice: what value to assign the inequality aversion parameter η. The figure keeps the mortality damage function, normalization region, and ρ fixed at their preferred values while allowing η to range from 0.75 to 1.75. The value for η corresponding to a 2% near-term discount rate ($\eta = 1.24$) is highlighted in red. The top panel shows results under the preferred Bressler et al. (2021) damage function while the bottom panel shows results under the Cromar et al. (2022) damage function. Under both damage functions, the SCC increases with inequality aversion despite greater rates of inequality aversion yielding greater discount rates. Larger values of η result in a more right-skewed distribution of SCC estimates because there is more curvature in the utility function, placing higher weight on bad outcomes across time and space. The more right-skewed the distribution, the greater the spread between median and mean values of the SCC. Indeed, under the Bressler et al. (2021) damage function, the median SCC estimates are nonlinear in response to an increase in inequality aversion.

Figure 10 shows the impact of the third choice: what region to use as the reference region. The figure now keeps the mortality damage function and discount factor constant while varying the reference region from low- to high-income countries. As Nordhaus (2011) discusses, the country or region to which equity weighted SCC estimates are normalized should reflect which country or region will bear the costs of emissions reductions. For example, using the US as the reference region is appropriate if the cost of emissions reductions will be borne by individuals in the US: the SCC is converted from welfare units to money as money is valued on the margin by individuals in the US. Under the Bressler et al. (2021) damage function, this "US" or "high-income country" calibration dramatically increases the SCC to \$2,466 compared to the preferred specification of \$504. The distribution of SCC estimates across the 10,000 Monte Carlo simulations is also least concentrated, with a 5%–95% quantile range from \$156 to \$6,234. My preferred equity weighted specification uses the world or "the globe" as the reference region. This distribution of SCC estimates is more concentrated, with a 5%–95% quantile range from \$30 to \$1,233. Since GDP per capita in China is very close to global GDP per capita, using China as the reference region yields very similar results to the preferred specification. Finally, when using Congo and the Philippines as the reference regions, the equity weighted SCC decreases dramatically from \$504 to \$154 and \$210, respectively. In addition, the distribution of SCC estimates is far more concentrated when using a low-income country as the reference region. The 5%–95% quantile ranges for Congo and the Philippines are [\$7, \$392] and [\$13, \$544].

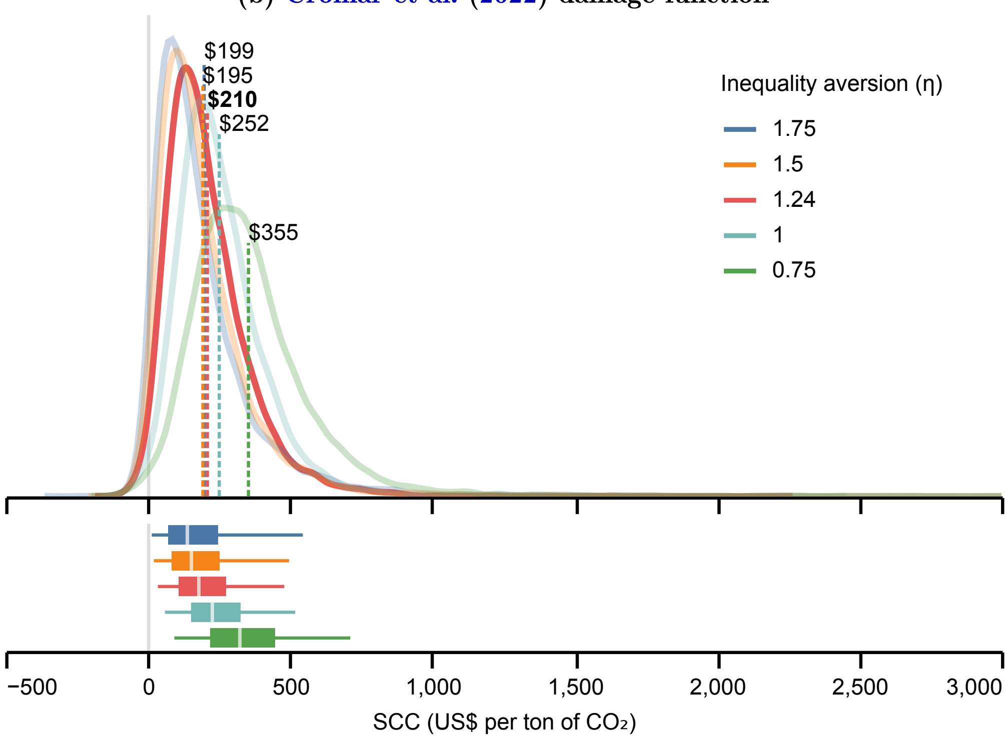
In sum, it is important to evaluate equity weighted results according to these three choices in order to understand whether they are driven by the distribution of impacts or simply by a large value of η or a high-income reference region. The equity weighted SCC increases substantially less under the Cromar et al. (2022) damage function than under the Bressler et al. (2021) damage function because high-income countries experience disproportionately high mortality damages.

Figure 9: Estimates of the equity weighted SCC vary with inequality aversion

(a) Bressler et al. (2021) damage function



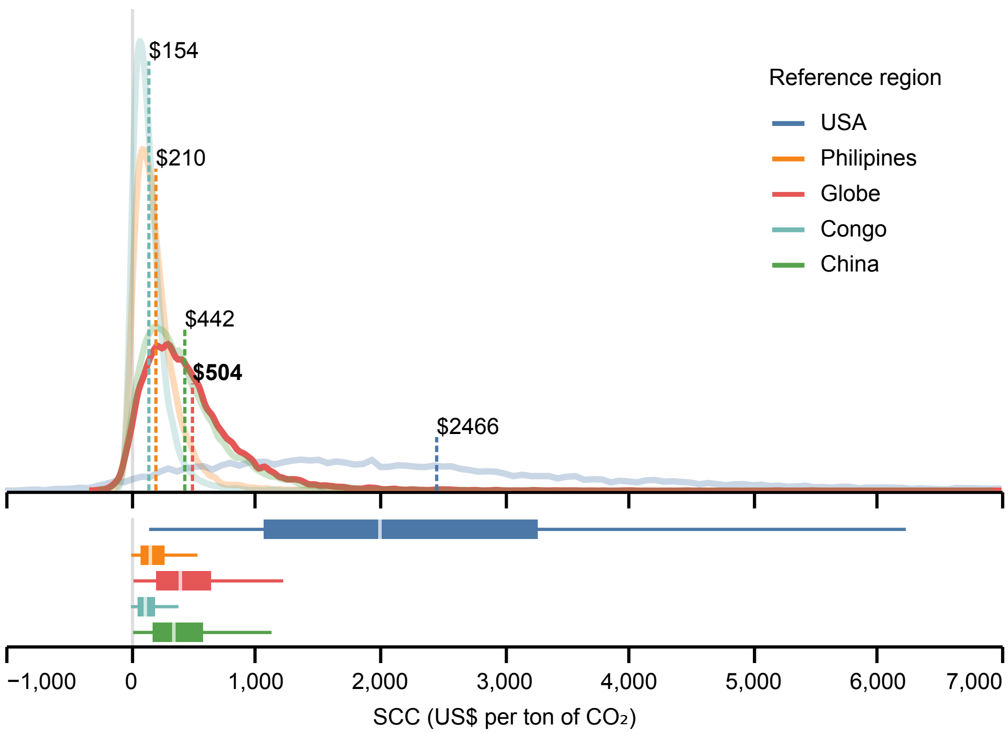
(b) Cromar et al. (2022) damage function



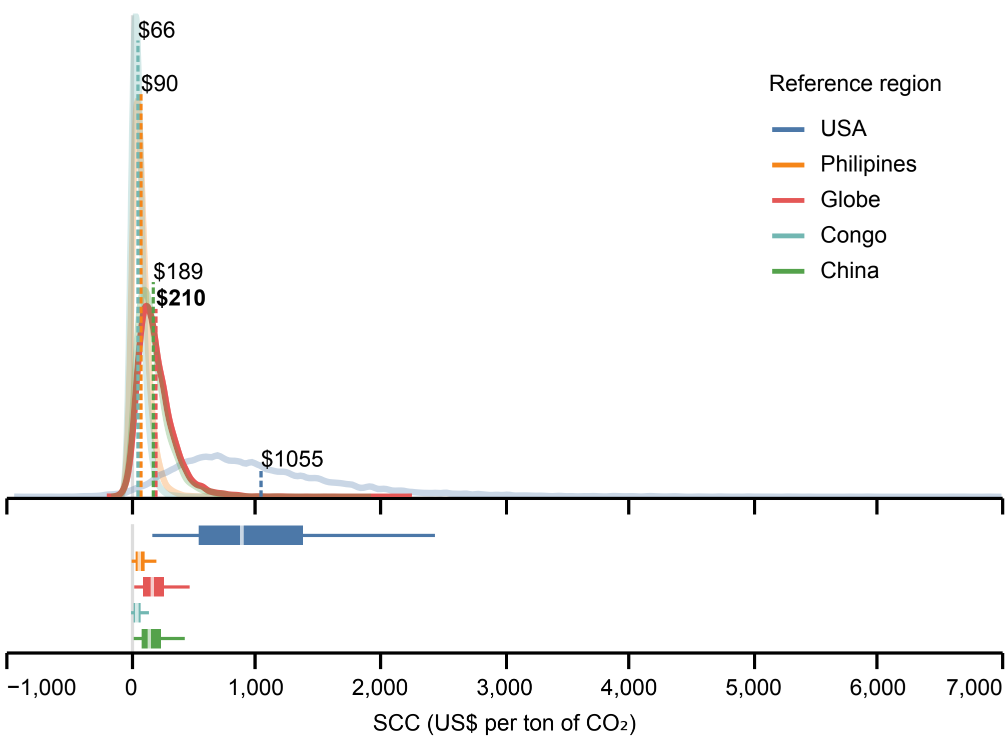
Notes: Figure shows distributions of the SCC based on the value of η. The reference region is held constant as the globe. The η value corresponding to a 2% near-term discount rate is highlighted in red. Dashed vertical lines highlight mean SCC values. Box and whisker plots along the bottom of the figure show the median of each SCC distribution (center white line), 25%–75% quantile range (box width), and 5%–95% quantile range (colored horizontal lines) values. Figure code adapted from Rennert et al. (2022).

Figure 10: Estimates of the equity weighted SCC vary with reference region

(a) Bressler et al. (2021) damage function



(b) Cromar et al. (2022) damage function



Notes: Figure shows distributions of the SCC based on the equity weighting reference region. The preferred equity weighting reference region, the globe, is highlighted in red. Dashed vertical lines highlight mean SCC values. Box and whisker plots along the bottom of the figure show the median of each SCC distribution (center white line), 25%–75% quantile range (box width), and 5%–95% quantile range (colored horizontal lines) values. Figure code adapted from Rennert et al. (2022).

7 Conclusion

The updated SCC has the potential to be one of the most powerful tools to address climate change. The increase from $51 to $190 will allow for increased stringency of the major rules already using the SCC in the calculation of their benefits.[46] It may also motivate an entirely new set of standards that were not calculated to be beneficial under the $51 estimate. Further, the 14 states currently using the SCC may update their SCCs to match the new national value (Institute for Policy Integrity, 2022). Stringent executive branch regulations and aggressive state-level policies are necessary to meet our target of 50-52% emissions reductions relative 2005 levels by 2030 (Rhodium, 2022). Such policies act as a complement to the Biden administration's recent demand-side investments. Further, beyond the direct importance of an increased SCC to meeting our climate targets, an accurate SCC is necessary to fulfill a fundamental role of government: to identify and account for market failures (OMB, 2023c).

The updated SCC reflects a novel and improved methodology. But a novel methodology introduces a novel set of questions. This senior essay addresses the hidden ethical assumptions in the calculation of global mortality damages. I argue that EPA's attempt to adhere to the Kaldor-Hicks principle may put the updated SCC in political and legal jeopardy. It is indeed a so-called "ethics nightmare" (Hersher et al., 2023). Is it defensible to discount the mortality impacts of climate change for individuals in low-income countries? The EPA's implicit answer to this question is "yes." They attempt to adhere to the Kaldor-Hicks criterion without considering the assumption of potential compensation in the context of climate change. This is not simply a passive extension of previous practice. In fact, this is the first time in two decades that the US government has assigned different-dollar VSLs to individuals based on their income, though in the past assignment has only been within the US. We must consider whether the inclusion of mortality damages outside the US justifies a change in our

[46] These rules include appliance energy efficiency regulations, vehicle greenhouse gas emission standards, corporate average fuel economy (CAFE) standards, and stationary source CO_2 emissions guidelines (EPA, 2022).

methodology.

This senior essay proposes two alternative approaches to the EPA's approach: extending the status quo approach to use a global average VSL and equity weighting. Both of these alternatives assign equal value to statistical lives. I argue that equity weighting is the first-best approach in terms of theoretical consistency but may be legally vulnerable—both before the new Circular A-4 is finalized and perhaps even after. A global extension of the status quo approach offers a middle ground by avoiding the potential political consequences associated with the use of an income-elastic VSL without necessitating an overhaul of the process of estimating the SCC.

I use the GIVE model to evaluate how these two alternative approaches affect the SCC. Using a global average VSL increases the SCC by 65% while equity weighting increases it by 118%. These results are driven by the distribution of mortality damages. Using a global average VSL or equity weighting increases the value of avoided mortality risk for individuals in low-income countries. My substitution of the Cromar et al. (2022) mortality damage function with the Bressler et al. (2021) mortality damage function increases estimated damages in these countries and therefore increases the SCC. It is worth stressing the rather straightforward conclusion from this exercise: an accurate mortality damage function is just as important as an appropriate monetization strategy.

Though equity weighting is not my preferred specification, I evaluate the sensitivity of equity weighted results to differences in key parameters given it could become standard practice in the future. The SCC increases with inequality aversion and with the income of the region to which weights are normalized. There is a strong argument for equity weighting with US income rather than global average income given that mitigation is paid for by individuals in the US. Indeed, the draft revised guidelines in Circular A-4 recommend equity weighting with US average income—though they do not explicitly state if this also applies to the analysis of damages outside the US (OMB, 2023a). Regardless, equity weighting with US average income increases the SCC by almost five times. Such a high SCC value may be politically unpalatable even if it is theoretically appealing.

Many important questions remain for future work. Damages from several sources are missing in the GIVE model, including changes in the demand for water resources, changes in ecosystem services, and the productivity of the livestock, aquaculture, and forestry industries (EPA, 2022). Further, damage categories already represented in GIVE are only partial accounts of total sectoral damages. Both mortality damage functions used in this senior essay only include temperature-related mortality and exclude a variety of mortality impacts (e.g., climate mediated changes in storms, wildfire, flooding, air pollution) and morbidity impacts (e.g., infectious diseases, malnutrition, allergies) (EPA, 2022). Further, they do not explicitly account for migration responses, humidity, technological change, or adaptation.

Finally, as climate models continue to improve, the academic and policy communities should continue to engage in open debate on how to account for the distribution of outcomes. The case for equity weighting the SCC is strengthened by the publication of new damage functions at much finer geographic resolutions. Incorporating such studies into GIVE along with more detailed income data would enable equity weighting to better approximate the utility individuals derive from avoided climate damages. Further, if the proposed revisions to Circular A-4 pass public comment and peer review, equity weighting will be permitted—and even encouraged—in future benefit-cost analyses. Until then, however, a global extension of the status quo is an ethically meaningful interim approach.

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APPENDIX

Intragenerational Equity in the Social Cost of Carbon

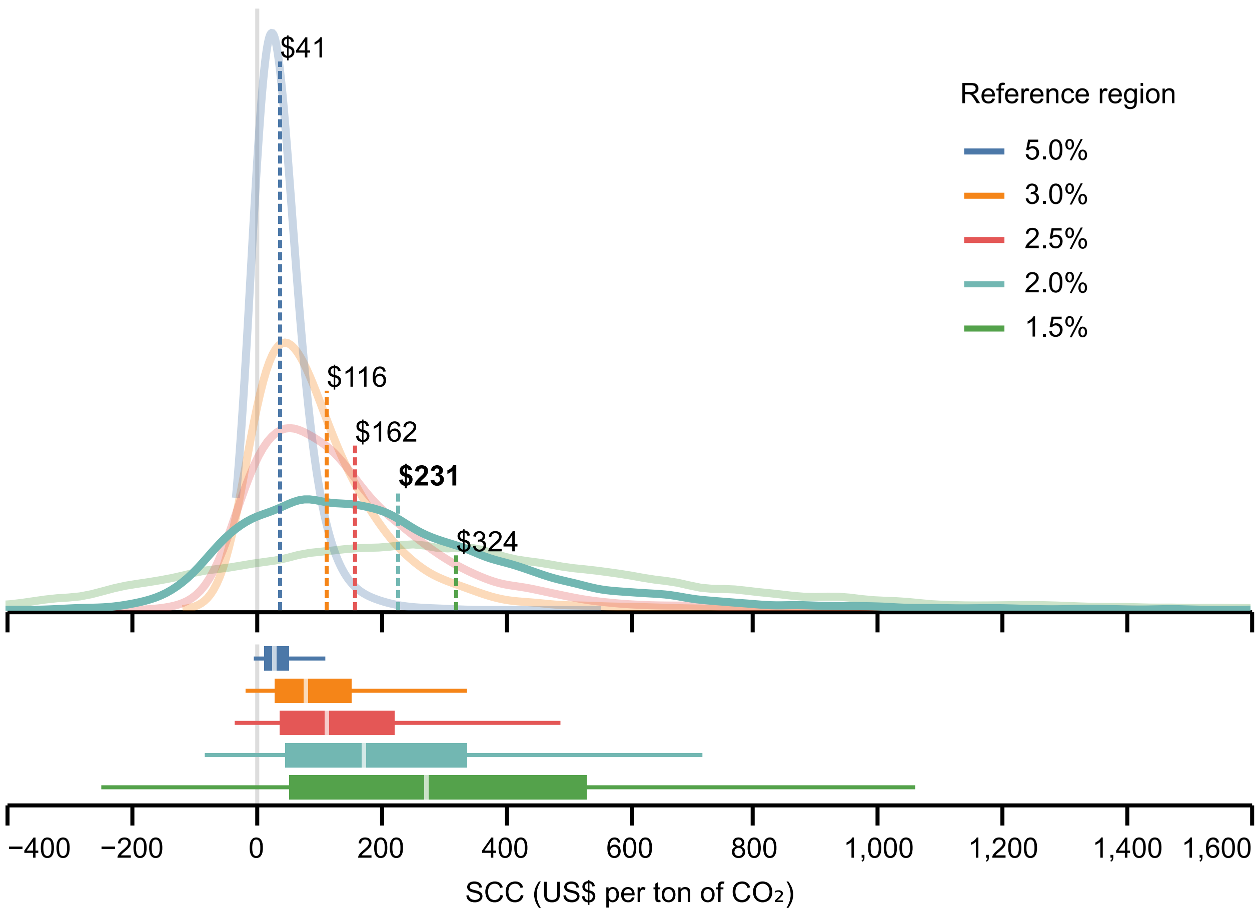
A Appendix: Additional results

This section presents additional results to show the robustness of the conclusions in the main text. Figure A.1 shows the distribution of SCC estimates using a country level VSL. It compares the discount rates used in the main text (1.5%, 2.0%, 2.5%) to 3% and 5% discount rates. The mean SCC is $116 under 3% discount rate and $41 under a 5% discount rate. The 5%–95% quantile ranges are [$-14, $342] and [$-1, $114], respectively.

Tables A.1-A.3 show mean SCC estimates under different socioeconomic and emissions pathways. Table A.1 shows results under the main Bressler et al. (2021) damage function, Table A.2 shows results for the Bressler et al. (2021) damage function without income protection from heat vulnerability, and Table A.3 shows results for the Cromar et al. (2022) mortality damage function. Each table shows results estimating using a country-level VSL (Panel A), global average VSL (Panel B), and equity weighting (Panel C).

The partial mortality SCC is systematically the lowest under SSP-RCP 1-2.6 across all three variants of the damage functions. Note that the mean partial mortality SCC is negative under the Bressler et al. (2021) mortality damage function with a 2% discount rate in this specification (Table A.1). The model projects that the reduction in the number of deadly cold days combined with the benefits of income growth will outweigh the increase in number of deadly hot days. The partial mortality SCC is systematically highest under SSP-RCP 3-7.0, a high emissions, low income scenario.

Figure A.1: The distribution of SCC estimates varies by discount rate



Notes: Figure shows distributions of SCC estimates under a country-level VSL for a variety of discount rates. Box and whisker plots along the bottom of the figure show the median of each SCC distribution (center white line), 25%–75% quantile range (box width), and 5%–95% quantile range (colored horizontal lines) values. All SCC values are expressed in 2020 US dollars per metric ton of CO2. Figure code adapted from Rennert et al. (2022).

Table A.1: Estimates of the mortality partial SCC under Bressler et al. (2021)

	Near-term discount rate		
	$r = 1.5\%$ (1)	$r = 2\%$ (2)	$r = 2.5\%$ (3)
Panel A: Country-level VSL			
RFF-SPs (moderate emissions, moderate income)	171.8	137.9	102.5
	(3.5)	(2.1)	(1.5)
SSP-RCP 1-2.6 (Low emissions, moderate income)	-82.5	-15.8	5.2
	(1.7)	(0.8)	(0.4)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	28	43.1	41.2
	(2)	(0.9)	(0.5)
SSP-RCP 3-7.0 (High emissions, low income)	672.6	431.3	275.9
	(3.8)	(2.3)	(1.4)
Panel B: Global average VSL			
RFF-SPs (moderate emissions, moderate income)	399.8	286.7	203
	(4.2)	(2.8)	(1.9)
SSP-RCP 1-2.6 (Low emissions, moderate income)	-31.5	12.8	24.5
	(1.7)	(0.8)	(0.4)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	82.8	80.2	69.6
	(1.9)	(0.9)	(0.5)
SSP-RCP 3-7.0 (High emissions, low income)	817.8	535.6	352.2
	(4.3)	(2.7)	(1.7)
Panel C: Equity weighted			
RFF-SPs (moderate emissions, moderate income)	429.2	376.3	320
	(23.4)	(6.6)	(3.3)
SSP-RCP 1-2.6 (Low emissions, moderate income)	-26.9	25	43.6
	(1.7)	(0.8)	(0.4)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	83.7	101	106.4
	(1.9)	(0.9)	(0.5)
SSP-RCP 3-7.0 (High emissions, low income)	815.7	601.9	463.7
	(4.4)	(3)	(2.2)

Notes: All mortality partial SCC values are expressed in 2020 US dollars per metric ton of CO2 and represent the mean value from 10,000 Monte Carlo simulations. Parentheses show the uncertainty standard error. An income elasticity of 1 is used to scale the U.S. EPA VSL value under the country-level and equity weighted approaches.

Table A.2: Estimates of the mortality partial SCC under Bressler et al. (2021) without income protection from heat vulnerability

	Near-term discount rate		
	$r = 1.5\%$ (1)	$r = 2\%$ (2)	$r = 2.5\%$ (3)
Panel A: Country-level VSL			
RFF-SPs (moderate emissions, moderate income)	850.8	461.8	272.6
	(4.6)	(2.6)	(1.6)
SSP-RCP 1-2.6 (Low emissions, moderate income)	591.4	271.9	144.7
	(2.7)	(1.2)	(0.6)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	931.2	416.3	217.3
	(4.4)	(1.9)	(0.9)
SSP-RCP 3-7.0 (High emissions, low income)	1448.6	876.3	525
	(7.2)	(4.2)	(2.5)
Panel B: Global average VSL			
RFF-SPs (moderate emissions, moderate income)	1117.8	616.9	371.7
	(5.8)	(3.4)	(2.2)
SSP-RCP 1-2.6 (Low emissions, moderate income)	572.4	282.2	161.2
	(2.5)	(1.2)	(0.7)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	922.4	440.5	246.4
	(4.3)	(2)	(1.1)
SSP-RCP 3-7.0 (High emissions, low income)	1592.3	988.4	611.7
	(7.9)	(4.8)	(2.9)
Panel C: Equity weighted			
RFF-SPs (moderate emissions, moderate income)	1134.2	741	525.4
	(6.1)	(4.2)	(3.2)
SSP-RCP 1-2.6 (Low emissions, moderate income)	573.7	305.3	193.7
	(2.5)	(1.3)	(0.8)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	928.6	474.8	301.2
	(4.3)	(2.1)	(1.3)
SSP-RCP 3-7.0 (High emissions, low income)	1595.3	1081	761.2
	(8)	(5.3)	(3.6)

Notes: All mortality partial SCC values are expressed in 2020 US dollars per metric ton of CO2 and represent the mean value from 10,000 Monte Carlo simulations. Parentheses show the uncertainty standard error. An income elasticity of 1 is used to scale the U.S. EPA VSL value under the country-level and equity weighted approaches.

Table A.3: Estimates of the mortality partial SCC under Cromar et al. (2022)

	Near-term discount rate		
	$r = 1.5\%$	$r = 2\%$	$r = 2.5\%$
	(1)	(2)	(3)
Panel A: Country-level VSL			
RFF-SPs (moderate emissions, moderate income)	150.6	87.2	55.3
	(0.6)	(0.4)	(0.3)
SSP-RCP 1-2.6 (Low emissions, moderate income)	80.6	41.5	24.8
	(0.3)	(0.1)	(0.1)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	108.1	55.9	33.7
	(0.4)	(0.2)	(0.1)
SSP-RCP 3-7.0 (High emissions, low income)	161.4	104.5	68.3
	(0.6)	(0.4)	(0.2)
Panel B: Global average VSL			
RFF-SPs (moderate emissions, moderate income)	133.4	77.2	48.9
	(0.6)	(0.4)	(0.2)
SSP-RCP 1-2.6 (Low emissions, moderate income)	87.4	43	24.7
	(0.4)	(0.2)	(0.1)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	111	55.1	32.2
	(0.4)	(0.2)	(0.1)
SSP-RCP 3-7.0 (High emissions, low income)	149.4	95.8	61.9
	(0.6)	(0.4)	(0.3)
Panel C: Equity weighted			
RFF-SPs (moderate emissions, moderate income)	133.3	83.8	58.1
	(1.7)	(0.6)	(0.3)
SSP-RCP 1-2.6 (Low emissions, moderate income)	87.4	45.8	27.4
	(0.4)	(0.2)	(0.1)
SSP-RCP 2-4.5 (Moderate emissions, moderate income)	111	57.6	35.2
	(0.4)	(0.2)	(0.1)
SSP-RCP 3-7.0 (High emissions, low income)	149.4	99.1	67.7
	(0.6)	(0.4)	(0.3)

Notes: All mortality partial SCC values are expressed in 2020 US dollars per metric ton of CO2 and represent the mean value from 10,000 Monte Carlo simulations. Parentheses show the uncertainty standard error. An income elasticity of 1 is used to scale the U.S. EPA VSL value under the country-level and equity weighted approaches.