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Abstract

The social cost of carbon (SCC) is a monetary measure of the harms from carbon emission. Specifically, it is the reduction in current consumption that produces a loss in social welfare equivalent to that caused by the emission of a ton of CO2. The standard approach is to calculate the SCC using a discounted-utilitarian social welfare function (SWF)—one that simply adds up the well-being numbers (utilities) of individuals, as discounted by a weighting factor that decreases with time. The discounted-utilitarian SWF has been criticized both for ignoring the distribution of well-being, and for including an arbitrary preference for earlier generations. Here, we use a prioritarian SWF, with no time-discount factor, to calculate the SCC in the integrated assessment model RICE. Prioritarianism is a well-developed concept in ethics and theoretical welfare economics, but has been, thus far, little used in climate scholarship. The core idea is to give greater weight to well-being changes affecting worse off individuals. We find substantial differences between the discounted-utilitarian and non-discounted prioritarian SCC.

JEL-Codes: Q540.

Keywords: social cost of carbon, climate change, prioritarianism, integrated assessment model, welfare economics.

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ARTICLE TEXT

Evaluating climate policy requires a method for navigating trade-offs, for example by balancing costs and benefits. The most systematic such method is the "social welfare function" (SWF) approach, which is widely used in the economic analysis of climate change[1–4], as well as many other areas of economics[5–8]. The core idea of the SWF approach is to convert information about an individual's attributes (material consumption, health, longevity, environmental conditions, etc.) into a univariate measure of individual *well-being*, using some well-being function $u(.)$. The status quo can then be represented as a pattern of individual well-being numbers, and policy choices as perturbations to this pattern.

Various formulas can be used to compare well-being patterns. By far the dominant approach in scholarship on climate policy is to use a *discounted-utilitarian* SWF[3]. Well-being numbers are multiplied by a weighting factor which decreases over time (sometimes referred to as a "utility discount factor" or as "pure time preference"). These time-discounted well-being numbers are then added up. The best policy maximizes the sum of time-discounted well-being.

Although widely used, the discounted-utilitarian SWF is controversial. At least two powerful criticisms have been raised against it. First, the use of the time-discount factor violates the ethical axiom of impartiality[9]. Harms and benefits to the members of later generations are downweighted in the social calculus by virtue of the ethically arbitrary fact that these individuals come into existence later in time. In a pioneering 1928 article on intertemporal social planning, Frank Ramsey wrote that time discounting is "ethically indefensible and arises merely from the weakness of the imagination"[10]. Other leading scholars have voiced the same criticism[4,11–17].

Second, quite apart from the issue of time-discounting, the utilitarian SWF ignores the distribution of well-being. Consider two hypothetical societies. Let U be a low level of well-being. In the first society, half the society is at level U, while the other half is much better off, at $3U$. In a second, equally sized but perfectly egalitarian society, everyone is at level $2U - \varepsilon$. The utilitarian SWF says that the first society is better, for *any* value of ε greater than 0. Many find this to be a troubling conclusion[18]. If we consider not only efficiency (total well-being), but also equity (fair distribution), it seems quite plausible that the second society is better for at least some range of positive ε.

Here, we explore the implications for climate policy of a different type of SWF: the non-discounted "prioritarian" SWF[7,19]. The key idea of "prioritarianism" is to give greater weight to well-being changes affecting worse off individuals. This is accomplished by summing well-being numbers transformed via a concave transformation (see Figure 1).

[Insert Figure 1 here. All figures are in the Figures section at the end of this document.]

The non-discounted prioritarian SWF avoids the two criticisms of utilitarianism discussed above. This SWF lacks a time discount factor and is thus impartial between generations. Moreover, the non-discounted prioritarian SWF gives greater weight to a well-being benefit incurred by a worse-off individual, and thus prefers an equal distribution of well-being to an unequal distribution of the same total amount.

There is now a substantial body of scholarship on the topic of prioritarianism, in academic philosophy[20–27] and theoretical welfare economics[6,28,29]. The chapter of the most recent Intergovernmental Panel on Climate Change (IPCC) report on ethical concepts and methods discusses prioritarianism at some length[30]. However, very little work has been yet undertaken to see what a non-discounted prioritarian SWF would recommend for climate policy, and how these recommendations differ from those of discounted utilitarianism.

We begin to fill this gap by comparing the discounted-utilitarian and non-discounted prioritarian SWFs with respect to a key aspect of climate policy—the "social cost of carbon" (SCC)[31–35]. The SCC is the reduction in the income of the current generation which is equally costly, in terms of social welfare, as the harms caused by emitting a ton of CO_2. The SCC can be used to specify a carbon tax, or to determine whether the emission caps in a cap-and-trade policy are too permissive. The US government now uses the SCC to calculate the climate impact of all major regulations[32,36]. Specifically, we calculate and compare the discounted-utilitarian and non-discounted prioritarian SCCs with the integrated assessment model RICE, arguably the most widely used numerical model that can estimate the SCC and has a regional structure[37].

Our analysis develops the prioritarian framework for climate economics, and advances the understanding about the SCC in an area that has been identified as a research priority[38]. It also contributes to a broader conversation about the importance of equity considerations in climate policy[39–43]—a point emphasized by Piketty, famous for his book on income inequality, who has more recently examined the distribution of carbon emissions and proposed a progressive carbon tax[44,45].

Utilitarianism, Prioritarianism, and the Social Cost of Carbon: Concepts and Parameter Ranges

A major debate among climate scholars concerns whether the specification of an SWF is "descriptive" or "normative"[9,17,46–48]. The former approach seeks to avoid ethical judgments, while the latter approach frankly incorporates such judgments. We adopt the normative approach in this paper. Although some SWF parameters may be identifiable from empirical observation (see below, discussing the individual risk-aversion parameter), others may not be, and the basic choice of functional form for an SWF is an ethical, not descriptive matter. Scientific observation and economic analysis cannot "demonstrate" that a particular SWF is "correct" or "incorrect." Rather, science and economics are important in clarifying the implications of various normative frameworks that policymakers or citizens may find normatively appealing[49]—such as utilitarianism or prioritarianism.

We follow the standard approach in climate economics and express well-being as a function of individual consumption. (An individual's "consumption" is the amount of money that she expends on marketed goods and services, and is often proxied by her income.) In this approach, effects on non-consumption attributes (for example, health harms from global warming) are assumed to be representable by equivalent consumption changes. The IAM we consider divides the world into regions. Let C_{tr} be the total consumption of region *r* at time *t*, and P_{tr} its total population. With these inputs, the discounted-utilitarian (DU) SWF, denoted W^{DU}, is defined in equation (1).

$$(1)\ W^{DU}=\sum_{t=1}^{T}\sum_{r=1}^{R}P_{tr}\times u(\frac{C_{tr}}{P_{tr}})\times\frac{1}{(1+\rho)^{t-1}}$$

Again in accordance with standard practice, we use a constant-relative-risk-aversion (CRRA) well-being function $u(c) = (1-\eta)^{-1}c^{1-\eta}$ or log *c* for $\eta = 1$ [1,3,4,9,50]. The η parameter is estimated by looking at evidence of individual preferences. Specifically, η is a measure of an individual's risk aversion with respect to consumption gambles—her willingness to incur a risk of lower consumption levels for the chance of higher ones[51].

This approach to specifying the well-being function rests upon a prior normative commitment to a non-paternalistic view of well-being, the view embraced by welfare economics: that an individual's well-being depends upon her preferences. Substantial behavioral evidence suggests a range of η between 0 and 3, and this is consistent with the range used in climate economics. See Methods for a fuller discussion. We use a range of 0 to 3 for η, with 1 as the central value.

The parameter ρ represents pure time preference. Stern advocates $\rho = 0$ (except for extinction risk)[4,46]; Nordhaus [1,48] sets $\rho = 1.5\%$; Weitzman suggests $\rho = 2\%$ [52]. In a survey of 197 experts on social discounting, Drupp *et al.*[47] find a median value of 0.5%, a mean of 1.1%, and a standard deviation of 1.47%. Our analysis considers a range of 0 to 3% for ρ, with 1% as the central value.

The non-discounted prioritarian SWF, which we are comparing to the standard discounted-utilitarian approach, is denoted W^{NP} and uses equation (2).

$$(2)\ W^{NP}=\frac{1}{1-\gamma}\sum_{t=1}^{T}\sum_{r=1}^{R}P_{tr}\left(u(\frac{C_{tr}}{\mathrm{P}_{tr}})-u(c^{zero})\right)^{1-\gamma}\quad\text{, with } \gamma > 0 \text{ (except } \gamma = 1\text{) or}$$

$$\sum_{t=1}^{T}\sum_{r=1}^{R}P_{tr}\log\left(u(\frac{C_{tr}}{\mathrm{P}_{tr}})-u(c^{zero})\right)\ \text{for } \gamma = 1$$

In its most general formulation, the non-discounted prioritarian SWF sums individual well-being numbers transformed by a strictly increasing and concave function *g*(.), as in Figure 1. Equation (2) uses a power function for *g*(.), with $g(u^*)=(1-\gamma)^{-1}(u^*)^{1-\gamma}$. The power function is especially attractive axiomatically, as compared to other functional forms for *g*(.) [7,19]. The parameter γ captures the degree of priority for individuals at lower well-being levels. This parameter can take any positive value (with $\gamma = 0$ the SWF becomes utilitarian), and a larger value of γ indicates a greater degree of priority for the worse off.

u^* is a measure of individual well-being that is unique up to a ratio transformation. This is accomplished, in equation (2), by using the constant relative risk aversion (CRRA) well-being function and then rescaling by setting $u^*(c) = u(c) - u(c^{zero})$ [7,19]. See Methods for further discussion of this rescaling and the c^{zero} parameter.

Parameter γ is a pure ethical parameter. Ethical intuitions about a normatively appropriate level of γ can be sharpened via various thought experiments, such as "leaky transfer" thought experiments[7]. Assume that the ratio between the well-being of two individuals is $K > 1$. Consider a policy that produces a small loss to the well-being of the better-off individual, with a benefit to the worse-off individual that is some fraction f of that loss. This "leaky transfer" is seen as a net improvement by the non-discounted prioritarian SWF if $f > (1/K)^{\gamma}$. Note that the acceptable degree of leakage $(1 - f)$ increases as γ increases. See Methods for a fuller discussion of thought experiments for ethical deliberation about the value of γ. In our analysis, we use a range of 0 to 3 for γ, with 1 as our central value.

Parameter c^{zero} is constrained to be greater than zero, but no greater than the lowest average regional consumption observed for all regions and times (see Methods). Within this range, the choice of c^{zero} is, again, an ethical matter. Consider some individual at a given consumption level, and a worse-off individual at a lower level. As this lower level approaches c^{zero}, the well-being ratio K between the better and worse off individual increases without bound, and thus the acceptable degree of leakage for a well-being transfer between them approaches unity. The level c^{zero} is a consumption level so low that those in its vicinity come close to a kind of absolute priority over more fortunate persons[19]. It is an ethical question what that level is. One natural thought is that c^{zero} is the *subsistence* level of consumption, below which ongoing existence is seriously at risk. We therefore set our central value of c^{zero} equal to \$500, suggested by the \$1.25/day and more recently \$1.90/day level of extreme poverty identified by the World Bank[53].

We now turn to the social cost of carbon (SCC). Assume that a ton of emissions at present will cause aggregate damage to individuals in region r at time t that is equivalent (in terms of their well-being) to the aggregate loss of consumption ΔC_{tr} for region r at time t. Then the SCC is the change in present consumption for some specified region B (the "normalization region") with the same effect on social welfare as the stream of equivalent consumption changes caused by the ton of emissions[39]. In other words, the SCC translates emissions into an effect on social welfare, and then expresses *that* effect in terms of the change to the present consumption of the normalization region with the very same social welfare impact. The SCC is calculated using equation (3). This equation is expressed in terms of a generic social welfare function W. By combining equation (3) with equation (1) for the discounted-utilitarian SWF, we arrive at the discounted-utilitarian SCC ($\mathrm{SCC}^{\mathrm{DU}}$); by combining it, instead, with equation (2), we arrive at the non-discounted prioritarian SCC ($\mathrm{SCC}^{\mathrm{NP}}$).

$$(3)\ \mathrm{SCC}_B = \frac{\sum_{t=1}^{T}\sum_{r=1}^{R}\Delta C_{tr}\frac{\partial W}{\partial C_{tr}}}{\frac{\partial W}{\partial C_{1B}}}$$

The term $\frac{\partial W}{\partial C_{tr}}$ (the partial derivative of the SWF W as calculated with equation (1) or (2)), denotes the increase in social welfare per incremental dollar added to the total consumption of region r at time t.

Note that the SCC (be it utilitarian or prioritarian) *depends* on the choice of normalization region, as indicated by the "B" subscript to SCC in equation (3). This is because regions are heterogeneous in their per capita consumption, and thus in the social-welfare impact of a marginal dollar. In the case of an IAM with the whole world treated as one region, there is no need to specify a normalization region. However, with IAMs such as RICE, that operate at a finer scale of regional detail, this choice is critical.

The Discounted-Utilitarian and Non-discounted Prioritarian SCC

We illustrate the SCC with three normalization regions: the US, Africa, and a "World-Fair" normalization which is an aggregate of all the regions. The SCC calculated with the US as normalizing region would be used by a decision maker impartial between the US and other regions, and between present and future generations, and setting a price of carbon for policies whose costs are wholly borne by present US citizens. This is of course an ethical idealization; actual US policymakers might depart quite substantially from full ethical impartiality and set a different (lower) carbon price for policies expected to be "paid for" by US citizens. The US has relatively high consumption; Africa is the poorest region in RICE, and is chosen to illustrate the effect of a much lower per-capita income in the normalization region.

Finally, World-Fair assumes that the costs of mitigation policies are borne by the present generation but spread "fairly" across regions in proportion to total consumption. That is, equation (3*) is used instead of (3) to calculate the SCC.

$$(3^*)\ SCC_{WF} = \frac{\sum_{t=1}^{T}\sum_{r=1}^{R}\Delta C_{tr}\frac{\partial W}{\partial C_{tr}}}{\sum_{r=1}^{R}\pi_r\frac{\partial W}{\partial C_{1r}}}\ ,$$

with π_r equaling (C_{1r}/C_1), C_1 total global consumption in the first time step.

A fourth result, "Global," ignores regional differences in consumption. Let C_t and P_t denote, respectively, total global consumption and population at time t. The Global SCC calculation means that, in equations (1) through (3) above, the double summation over times and regions is replaced by a single summation over times, and C_t and P_t are substituted, respectively, for C_{tr} and P_{tr}. Global is used to facilitate comparison between our analysis and the many calculations of SCC in the literature that ignore regional differences in consumption.

All our results are in US dollars (2015 price levels) per ton of CO_2 emission. The RICE model uses "purchasing power parity" to convert foreign currency amounts into US dollars[54].

Recall that parameter η is the parameter of the well-being function, measuring individual risk aversion with respect to consumption gambles (used in both the discounted-utilitarian and non-discounted prioritarian SWF); ρ is the pure rate of time preference (used in the discounted-utilitarian SWF); and γ is the degree of priority for the worse off (used in the non-discounted prioritarian SWF). Figure 2 shows, in the left column, SCC^{DU} for the normalization regions US, Africa, and World-Fair, as well as the Global calculation, as a function of η and ρ.

[Insert Figure 2 and Figure 3 here]

In the right column of Figure 2 are displayed SCC^{NP} for those normalization regions and the Global SCC^{NP}, now as a function of η and γ, with c^{zero} set at the central value of \$500. In Figure 2, these results are displayed as 3 dimensional graphs. In Figure 3, the very same information is displayed, but in two-dimensional "contour" plots. Extreme values of SCC (meaning values above \$10,000) are truncated to \$10,000.

The parameter η is the one common parameter of the two SWFs, and thus of SCC^{DU} and SCC^{NP}. Figure 4 are one-dimensional sensitivity plots showing how SCC^{DU} and SCC^{NP} vary with η (given central values of the other parameters), for the three normalization regions and for Global.

[Insert Figure 4 here]

A number of key observations emerge from Figures 2 through 4. (1) Time-preference (ρ) and priority for the worse off (γ) both function to prevent extreme values of the SCC. With low values of the risk-aversion parameter η (at or near zero), the SCC^{DU} with $\rho = 0$ takes on extreme values for all normalization regions and Global. Holding constant η, increasing ρ reduces the SCC^{DU}. This is consistent with an argument sometime made in defense of positive time preference—namely, that zero time preference can require huge and intuitively unreasonable sacrifices from the present generation, to the extent their activities have effects on many future generations[1,48,52].

However, it is important to see that positive time preference is *not* the sole mechanism for mitigating sacrifices from the present generation. The SCC^{NP} also assumes extreme values with low values of η *if* γ is set to zero, but these values diminish—*without introducing a time preference*—as γ is increased moderately. Even with zero risk aversion $\eta = 0$, a very moderate level of the priority parameter $\gamma > 0.5$ suffices to avoid an extreme SCC. The intuition is that reducing the consumption of the present generation so as to mitigate climate impact makes the present generation worse off; and at a certain point a further sacrifice is not ethically recommended, by prioritarians, even if the cost to the present generation of that additional reduction would be smaller than the undiscounted sum of future benefits.

(2) Priority for the worse off (γ) is not time preference (ρ) under a different name. The time-preference parameter ρ of the discounted-utilitarian SWF and the priority parameter γ for the non-discounted prioritarian SWF are conceptually quite different. Nonzero values of ρ raise concerns about ethical neutrality between the generations that are not implicated by nonzero values of γ. Our analysis demonstrates that a shift from ρ to γ makes a *practical* difference (Figure 3). While γ and ρ do both function to mitigate extreme values of SCC for η near zero (as observed immediately above), SCC^{NP} as a function of γ for a given value of η is generally quite different (as γ ranges from 0 to 3) than SCC^{DU} as a function of ρ (with ρ ranging from 0 to 3%). This can be seen by comparing the color patterns across the rows in each of the four contour figures in the left column of Figure 3, with the patterns in the corresponding figures in the right column. Analytically, it can be shown that SCC^{DU} always decreases with an increasing rate of time preference, but that SCC^{NP} does not necessarily decrease with increasing γ (see Methods). Note that in the US, Global, and World-Fair normalizations, SCC^{NP} is little changed with increasing γ for larger values of η.

(3) At the central parameter values, the non-discounted prioritarian SCC is greater than the discounted-utilitarian SCC. This result refers to Figure 4—displaying SCC^{NP} with $\rho = 1$ and $c^{zero} = 500$, and SCC^{DU} with $\gamma = 1$, each calculated as a function of the common parameter η. In all cases, with η above the low level of 0.5, the SCC^{NP} is larger than SCC^{DU}—although the ratio between SCC^{NP} and SCC^{DU} never exceeds five and, as η increases, approaches or reaches unity. (With Africa as the normalizing region, SCC^{DU} exceeds SCC^{NP} for low η).

As an analytical matter, it is *not* obvious whether shifting from discounted utilitarianism to non-discounted prioritarianism will raise or lower the SCC. On the one hand, removing the time-discount factor will tend to raise the SCC; on the other hand, inserting a priority parameter will tend to lower the SCC, to the extent the normalizing region is worse off than future affected regions. In our modelling exercise based on the RICE model, we find that the net effect of these two changes is to increase SCC^{NP} relative to SCC^{DU}.

The magnitude of the SCC^{NP} values for the US normalizing region, which lie in the range \$1500 to \$3000, is—perhaps—surprising. Note, however, that SCC^{DU}-US values are also quite large, and that the choice of Africa or World-Fair normalization brings down the values substantially for both SCCs. The choice of normalization region clearly matters a great deal for both SCC^{DU} and SCC^{NP}. A dollar cost in the US doesn't have the same social-welfare impact as in Africa, or spread proportionately across the globe—in the case of the discounted-utilitarian SWF, because of the declining marginal utility of money (with $\eta > 0$); in the case of the non-discounted prioritarian SWF, because of that *and* the additional priority for the worse off that occurs with $\gamma > 0$. For similar reasons, the Global estimates of both SCC^{NP} and SCC^{DU} are much lower than the regionally disaggregated estimates with the US as normalizing region.

(4) Individual risk aversion (η), priority for the worse off (γ), and the zero level of consumption (c^{zero}) interact in complex ways to determine the magnitude of the prioritarian SCC. Our discussion, thus far, has focused on comparing discounted utilitarianism and non-discounted prioritarianism. We now briefly review the effect of the three parameters η, γ and c^{zero} within the prioritarian framework.

Analytically, the effect of γ on SCC^{NP} is complex: if the normalizing region (as with Africa or Global) is poorer at present than all future regions, SCC^{NP} will decrease as γ increases. But SCC^{NP} can, in principle, decrease or increase with γ with a richer normalizing region (US) or a composite normalization (World-Fair). Similar points hold true of c^{zero}. The effect of η on SCC^{NP} is yet more complex: even with a normalizing region that is worse off than future regions, SCC^{NP} might decrease or increase with η. Some of these non-monotonicities can indeed be observed in the contour figures in the right column of Figure 3. See Methods for analysis.

Figure 5 displays the SCC^{NP} as a function of c^{zero}, γ and η, in each case with the other parameters set at their central values.

[Insert Figure 5 here]

The impact of c^{zero} on SCC^{NP} is not trivial, but is clearly less substantial than that of η and γ. η and γ have a similar range and pattern of impact on SCC^{NP} for Africa, World-Fair, and Global, but not for US.

Conclusion

Climate change mitigation and adaptation policies cannot ignore distributional considerations. As emphasized by the recently approved Sustainable Development Goals, poverty and inequality are intimately connected to the problem of climate change; the issues cannot be sealed off from each other. We introduce a framework, prioritarianism, that seamlessly integrates distributional considerations—via a priority parameter (γ) specifying the degree of extra weight given to welfare changes affecting the worse off. We use the integrated assessment model RICE to show how the prioritarian social cost of carbon SCC is a function of γ as well as individual risk aversion η and a zero level of consumption c^{zero}—by contrast with the discounted-utilitarian SCC, which depends upon η and a time preference factor (ρ).

Not surprisingly, the level of γ is one major driver of the prioritarian SCC. Choosing this level is a normative judgment; such judgments cannot be avoided in climate policy. The utilitarian SCC, in effect, sets γ to zero—this too is a normative judgment, and one that is quite contestable.

METHODS

Range of Values of η

The CRRA well-being function is $u(c)=(1-\eta)^{-1}c^{1-\eta}$. Recent empirical studies on investment choices find support for such CRRA well-being functions[55,56]. If calibrated from individual preferences, this generally assumes that individuals have identical preferences over consumption gambles, parameterized by a common coefficient of relative risk aversion η. The empirical literature often finds estimated values for η between 0.5 and 3 [57–60]. A more nuanced well-being function would allow for heterogeneous preferences[19], with individual-specific values of η, but this has not been implemented in climate economics and is rarely done in SWF scholarship more generally[5]. IAMs, the climate discounting literature and recent works on the SCC generally use values in the [0.5, 3] range[9,32,52] with a most common value at η=1 [61–63].

The Specific Parameters of the NP SWF: c^{zero} and γ

What follows is a summary discussion of topics that are treated in detail in Adler[7], and Adler and Treich[19].

The CRRA well-being function is unique up to a positive affine transformation. Assume that $u(c)=(1-\eta)^{-1}c^{1-\eta}$ represents an individual's preferences with respect to consumption gambles. Then so does $u^+(c) = au(c) + b$, with *a* positive. This is a standard feature of so-called "expected utility" functions, such as the CRRA function[64].

The DU SWF is invariant to positive affine transformations of the well-being function. Let C_{tr} be the consumption of region *r* at time *t* in one state of the world; C_{tr}' its consumption in an alternative state; and $u^+(.)$ a positive affine transformation of $u(.)$. Note now that

$$\sum_{t=1}^{T}\sum_{r=1}^{R}P_{tr}\times u\left(\frac{C_{tr}}{P_{tr}}\right)\times\frac{1}{(1+\rho)^{t-1}}\geq\sum_{t=1}^{T}\sum_{r=1}^{R}P_{tr}\times u\left(\frac{C_{tr}'}{P_{tr}}\right)\times\frac{1}{(1+\rho)^{t-1}}$$

$$\Leftrightarrow$$

$$\sum_{t=1}^{T}\sum_{r=1}^{R}P_{tr}\times u^+\left(\frac{C_{tr}}{P_{tr}}\right)\times\frac{1}{(1+\rho)^{t-1}}\geq\sum_{t=1}^{T}\sum_{r=1}^{R}P_{tr}\times u^+\left(\frac{C_{tr}'}{P_{tr}}\right)\times\frac{1}{(1+\rho)^{t-1}} .$$

Further, this invariance property is independent of the issue of time-discounting; it holds true even if ρ is set to zero in the above equations, so that we have non-discounted utilitarianism.

By contrast, the NP SWF in the generic form of summing an increasing, concave function of individual well-being is *not* invariant to a positive affine transformation of the well-being function. Let $g(.)$ be any increasing, concave function. Then in general it is *not* the case that

$$\sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u(\frac{C_{tr}}{P_{tr}})) \geq \sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u(\frac{C_{tr}'}{P_{tr}}))$$

$$\Leftrightarrow$$

$$\sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u^{+}(\frac{C_{tr}}{P_{tr}})) \geq \sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u^{+}(\frac{C_{tr}'}{P_{tr}}))$$

However, it *is* possible for an NP SWF to be invariant to a positive *ratio* transformation of the well-being function. Let $u^{++}(.)$ be a positive ratio transformation of a given $u(.)$, i.e., $u^{++}(c) = au(c)$, with a positive. Then an NP SWF is invariant to a positive ratio transformation if the following holds true:

$$\sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u(\frac{C_{tr}}{P_{tr}})) \geq \sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u(\frac{C_{tr}'}{P_{tr}}))$$

$$\Leftrightarrow$$

$$\sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u^{++}(\frac{C_{tr}}{P_{tr}})) \geq \sum_{t=1}^{T}\sum_{r=1}^{R} P_{tr} \times g(u^{++}(\frac{C_{tr}'}{P_{tr}}))$$

It can be shown that an NP SWF has this ratio invariance property if and only if the $g(.)$ function has the power ("Atkinson") form: $g(u) = (1-\gamma)^{-1}u^{1-\gamma}$, with $\gamma > 0$. In the special case of $\gamma = 1$, $g(u) = \log u$.

Moreover, ratio invariance provides a powerful argument *for* the Atkinson $g(.)$, as compared with other $g(.)$ functions. If the NP SWF using a given $g(.)$ is *not* invariant to a positive ratio transformation, this means that two well-being functions $u(.)$ and $u^{++}(.)$ with identical information about well-being levels, differences, and ratios produce different rankings of outcomes when inputted into the SWF. But it is normatively implausible that an SWF should depend upon information above and beyond well-being level, difference, and ratio information.

Given some well-being function $u(.)$ unique up to a positive affine transformation, we identify a corresponding $u^*(.)$ unique up to a positive ratio transformation by identifying a "zero bundle." In the case where $u(.)$ is defined on individual consumption, this means, specifically, identifying a zero level of consumption, c^{zero}, and setting $u^*(c) = u(c) - u(c^{zero})$. Note that $u^*(.)$ preserves all of the information in $u(.)$ concerning well-being levels and differences.

To simplify the presentation, consider now the NP SWF of the Atkinson form defined in terms of the consumption amounts of N individuals (rather than in terms of regional total consumption and population). Let c_i be the consumption of individual i, and $u^*(c_i) = u(c_i) - u(c^{zero})$. Let $w(.)$ be the SWF, defined on a vector of N well-being numbers.

$w = w(u_1^*,\ldots,u_N^*) = w(u^*(c_1), \ldots, u^*(c_N)) = (1-\gamma)^{-1}\sum_i u^*(c_i)^{1-\gamma}$ or $w = \sum_i \log u^*(c_i)$ for $\gamma = 1$

For a given individual i, the marginal ethical impact of well-being, $\dfrac{\partial w}{\partial u_i^*}$, equals $(u_i^*)^{-\gamma}$ or, equivalently, $[u(c_i) - u(c^{zero})]^{-\gamma}$. The marginal ethical impact of consumption, $\dfrac{\partial w}{\partial u_i^*}\dfrac{du_i^*}{dc_i}$, equals $(u_i^*)^{-\gamma}\dfrac{du_i^*}{dc_i}$ or, equivalently, $[u(c_i) - u(c^{zero})]^{-\gamma}u'(c_i)$, with $u'(.)$ the first derivative of $u(.)$.

It is important to note that the Atkinson NP SWF requires well-being numbers to be non-negative. If $u_i^* < 0$, the function $(1-\gamma)^{-1}(u_i^*)^{1-\gamma}$ is either undefined or, if defined, not both increasing and concave. Note further that if $\gamma \geq 1$, the function is undefined with $u_i^* = 0$. We therefore require that $u_i^* > 0$.

These observations and formulas can be used to guide deliberation about the two parameters c^{zero} and γ. Consider first c^{zero}. The meaning of negative consumption is unclear; and the CRRA well-being function $u(c) = (1-\eta)^{-1}c^{1-\eta}$ ($\log(c)$ for $\eta = 1$) is undefined for $c = 0$ if $\eta \geq 1$. We therefore require that $c^{zero} > 0$. Conversely, c^{zero} must be *smaller* than any observed consumption amount in the outcomes being analyzed. Assume that there is some c_i such that $c_i \leq c^{zero}$. Then $u_i^* = u^*(c_i) = u(c_i) - u(c^{zero}) \leq 0$ (for any well-being function that increases with consumption, such as the CRRA function), in violation of the requirement that $u_i^* > 0$. Thus, as mentioned in the text, we require c^{zero} for our analysis to be positive but less than the smallest per-capita consumption (C_{tr}/P_{tr}) for any time-region pair.

Within this range, c^{zero} is such that it functions as a point of absolute ethical priority. Consider two individuals i and j with consumption amounts $c_i < c_j$, both greater than c_{zero}. The well-being ratio K, richer to poorer, is u_j^* / u_i^* . Note now that the ratio between the marginal ethical impact of *well-being* for the two individuals (the poorer individual in the numerator) is $(u_i^*)^{-\gamma} / (u_j^*)^{-\gamma} = (u_j^* / u_i^*)^{\gamma} = K^{\gamma} = \left(\dfrac{u(c_j) - u(c^{zero})}{u(c_i) - u(c^{zero})}\right)^{\gamma}$. As c_i gets closer and closer to c^{zero}, holding fixed c_j, K^γ approaches infinity and the ratio of marginal ethical well-being impacts approaches infinity.

The ratio between the marginal ethical impact of *consumption* for the two individuals is $\left(\frac{u(c_j)-u(c^{zero})}{u(c_i)-u(c^{zero})}\right)^\gamma \frac{u'(c_i)}{u'(c_j)}$. This ratio also approaches infinity as c_i gets closer and closer to c^{zero}, for the CRRA well-being function and any other such that well-being is increasing in consumption at a diminishing rate.

Consider now the specification of γ. "Leaky transfer" thought experiments are one method for doing so. Consider a policy that produces a small reduction Δu^* in the well-being of the better-off individual *j*; produces a small increase $f\Delta u^*$ in the well-being of the worse-off individual *i*, with $0 < f \leq 1$; and leaves everyone else's well-being unchanged. If $f=1$ (a "pure transfer"), the NP SWF sees the policy as an ethical improvement. We can now ask: what is the smallest value *f* for which the policy is an ethical improvement? Equivalently, what is the maximum ethically acceptable leakage rate, $1-f$? Note that the change in *w* produced by a loss of Δu^* by *j* is approximately $-(\Delta u^*)(u_j^*)^{-\gamma}$, while the change in *w* produced by a gain of $f\Delta u^*$ by *i* is approximately $(f\Delta u^*)(u_i^*)^{-\gamma}$—for small Δu^*— and so the smallest value of *f* is approximately $(u_i^*/u_j^*)^\gamma = 1/K^\gamma$, with the maximum acceptable leakage rate $1 - 1/K^\gamma$. For a fixed *K*, *f* decreases and the maximum acceptable leakage rate increases as γ increases. For example, if the better-off individual is at twice the level of well-being of the worse off individual, with γ =1 the maximum ethically acceptable leakage rate is 50%. With γ = 2 it becomes 75%, and with γ = 3 it is 87.5%. If the ratio increases to $K = 3$, then these maximum acceptable rates become, respectively, 67% (γ =1), 89% (2), and 96% (3).

To be sure, thought experiments in terms of transfers of well-being (u^*) between individuals at a given well-being ratio *K* have the advantage of being independent of a specific well-being function, but the disadvantage of being somewhat abstract. Alternatively, we can consider hypothetical leaky transfers of *consumption* between better- and worse off individuals. If a policy decreases individual *j*'s consumption by a small Δc, and increases *i*'s consumption by $f\Delta c$, the smallest value *f* for which the policy is an ethical improvement is approximately

$$\left(\frac{u(c_i)-u(c^{zero})}{u(c_j)-u(c^{zero})}\right)^\gamma \frac{u'(c_j)}{u'(c_i)}$$

. (This is just the inverse of the formula above for the ratio of marginal ethical impacts of consumption.)

Let's now assume a CRRA well-being function for *u* at the central value of η =1, i.e., $u(c) = \log c$, $u'(c) = 1/c$. If c^{zero} is 500, then *f* equals $\frac{[\log c_i - \log(500)]^\gamma}{[\log c_j - \log(500)]^\gamma}\frac{c_i}{c_j}$. For the sake of illustration, let c_j = \$40,000 (a moderately high level of individual annual income in the US) and

c_i = \$20,000 (an average level). Then with γ =1 the maximum acceptable leakage rate in income for a small income transfer to the worse off individual is 58%; with γ =2 it becomes 65%; with γ =3, 70%.

Several studies have attempted to estimate γ based on the "leaky transfer" thought experiment. These studies usually consider transfers in consumption or income rather than in utility, and estimate a so-called "inequality aversion" parameter that combines the effects of γ and η. For instance, Amiel *et al.*[65] conduct surveys for groups of students from two different countries, and find that the estimated median value for inequality aversion is between 0.1 and 0.2. An alternative approach is to present survey respondents with a choice between different income distributions in hypothetical options. In one of the options, the mean income is low and the income dispersion small; in another the mean income is higher but the income distribution more dispersed. Carlsson *et al.*[66], in their experiment with Swedish students, found that the median value for inequality aversion lies between 1 and 2. Using a representative sample of Finnish people, Pirtttila and Uusitalo[67] show that the median value for inequality aversion of the respondents in a leaky bucket case lies below 0.5, while it is larger than 3 in the preferred income distribution treatment. Moreover, they show that both measures of inequality aversion predict well the respondents' opinions on the proper role of the welfare state, such as the level of taxation, tax progressivity and the scope of unemployment benefits. There exist also some studies examining preference towards (in-)equality in health. There is ample evidence that utilitarianism is rejected in the health domain, and that people agree to give priority to the most severely ill[68]. Dolan *et al.* find estimates for inequality aversion in health that vary from 1.55 to 7.32 [69]. These studies are discussed in Adler (pp. 397-399)[7].

A different kind of thought experiment for specifying γ is an "equalization" thought experiment. Imagine that the policy equalizes the two individuals' well-being levels at some intermediate level U^*, without affecting anyone else's welfare. Let π be the ratio between the total well-being of the two individuals with the policy, and initially. That is, $\pi = 2U^*/(u_i^* + u_j^*)$. If $\pi \geq 1$, the policy is an ethical improvement for any NP SWF. We can now ask: what is the minimum value of π ($\pi^{\min}$) above which the policy remains an ethical improvement? $1-\pi^{\min}$ is the maximum acceptable percentage loss in the total welfare of the two individuals for the sake of perfect equalization. It can be shown that $1 - \pi^{\min}$ equals: $1-\frac{2}{1+K}\left(\frac{1+K^{1-\gamma}}{2}\right)^{1/(1-\gamma)}$ (or $1-2\sqrt{K}/(1+K)$ in the case of γ =1), which increases with γ.

This way of thinking about γ tends to make higher values seem less "extreme." For example, if K = 2, $1 - \pi^{\min}$ is 6% for γ =1; 11% for γ =2; and 15% for γ =3. If K =3, the values are 13% (γ=1), 25% (γ =2), and 33% (γ =3). Leaky transfer thought experiments involve *marginal* (small) transfers in well-being, and thus the maximum acceptable leakage approaches 100% as γ gets large; while equalization thought experiments involve *inframarginal* transfers in well-being, and the maximum acceptable percentage loss in total well-being is bounded above by 1 – 2/(1+K), i.e., 33% for K =2, 50% for K =3, etc.

Implementing the SCC in RICE

We use the integrated assessment models RICE for our numerical results. The RICE results were generated using a re-coded version of RICE called Mimi-RICE.jl that produces identical results as the original Excel version of RICE-2010 that was developed by Bill Nordhaus[37]. Mimi-RICE.jl is open source and will be made available on github.com at time of publication.

The RICE model is a standard integrated assessment model of climate change economics and has been widely used in the peer-reviewed literature and policy analysis. The model has simple natural science components that estimate the effect of emissions on temperature. It is regionally disaggregated and it estimates the welfare impacts of a change in climate for different regions of the world separately. A complete description of the model is beyond the scope of this article. We point the interested reader to the model documentation at http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm. The estimation of the SCC followed a simple procedure. We first estimated a matrix ΔC_{tr} of impacts caused by an additional ton of CO2 emission in the present. In a second step we used those estimates and the equations for the SCC that are derived in the next section (SCC$^{\mathrm{DU}}$ and SCC$^{\mathrm{NP}}$) to compute our results.

The matrix ΔC_{tr} for the model was created by running the model first for a business as usual scenario, and then for a second scenario with a small additional emission impulse in the present. The difference between consumption levels (net of impacts) between these two runs was recorded for each timestep and region as the ΔC_{tr} variable.

Analytical Results regarding the Parameters of the DU SWF

Recall that the SCC is defined as $\dfrac{\sum_{t=1}^{T}\sum_{r=1}^{R}\Delta C_{tr}\dfrac{\partial W}{\partial C_{tr}}}{\dfrac{\partial W}{\partial C_{1B}}}$. For the DU SWF (equation 1 in the main text), $\dfrac{\partial W}{\partial C_{tr}} = u'(\dfrac{C_{tr}}{P_{tr}}) \times \dfrac{1}{(1+\rho)^{t-1}} = (\dfrac{C_{tr}}{P_{tr}})^{-\eta} \times \dfrac{1}{(1+\rho)^{t-1}}$. To reduce clutter, let c_{tr} be per capita consumption in region r at t, i.e., C_{tr}/P_{tr}. Then we have that:

$$SCC^{DU} = \sum_{t=1}^{T}\sum_{r=1}^{R}\Delta C_{tr}(\frac{c_{1B}}{c_{tr}})^{\eta}\frac{1}{(1+\rho)^{t-1}} \ .$$

To see the effect of ρ and η on SCC^{DU}, consider, respectively $\frac{\partial SCC^{DU}}{\partial \rho}$ and $\frac{\partial SCC^{DU}}{\partial \eta}$.

It is straightforward from the above equation that $\frac{\partial SCC^{DU}}{\partial \rho}<0$, since $t \geq 1$ and $\rho \geq 0$ (zero or positive time discount).

$$\frac{\partial SCC^{DU}}{\partial \eta} = \sum_{t=1}^{T}\sum_{r=1}^{R}\Delta C_{tr} \times \frac{1}{(1+\rho)^{t-1}} \times (\frac{c_{1B}}{c_{tr}})^{\eta} \times \log(\frac{c_{1B}}{c_{tr}})$$

Note that every term in this formula following ΔC_{tr} is positive except $\log(c_{1\mathrm{B}}/c_{tr})$, which is negative if $c_{1\mathrm{B}} < c_{tr}$ and positive if $c_{1B} > c_{tr}$. Thus $\frac{\partial SCC^{DU}}{\partial \eta}$ is unambiguously negative iff per capita consumption in the normalization region at time 1 ($c_{1\mathrm{B}}$) is less than per capita consumption in every time/region pair that experiences a climate impact (every c_{tr} s.t. $\Delta C_{tr} > 0$).

Analytical Results regarding the Parameters of the NP SWF

For the NP SWF (equation 2 in the main text),

$$\frac{\partial W}{\partial C_{tr}} = [u(c_{tr}) - u(c^{zero})]^{-\gamma} u'(c_{tr}) = \left(\frac{c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}}{1-\eta}\right)^{-\gamma} c_{tr}{}^{-\eta}$$, assuming η≠1. Thus

$$SCC^{NP} = \sum_{t=1}^{T}\sum_{r=1}^{R}\Delta C_{tr}\left[\frac{c_{1B}{}^{1-\eta} - (c^{zero})^{1-\eta}}{c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}}\right]^{\gamma}\left(\frac{c_{1B}}{c_{tr}}\right)^{\eta}.$$

Consider, in turn, $\frac{\partial SCC^{NP}}{\partial \gamma}$, $\frac{\partial SCC^{NP}}{\partial c^{zero}}$, and $\frac{\partial SCC^{NP}}{\partial \eta}$.

$$\frac{\partial SCC^{NP}}{\partial \gamma} = \sum_{t=1}^{T}\sum_{r=1}^{R}\Delta C_{tr}\left[\frac{c_{1B}{}^{1-\eta} - (c^{zero})^{1-\eta}}{c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}}\right]^{\gamma}\left(\frac{c_{1B}}{c_{tr}}\right)^{\eta}\log\left(\frac{c_{1B}{}^{1-\eta} - (c^{zero})^{1-\eta}}{c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}}\right).$$

Note that the term $\left(\frac{c_{1B}{}^{1-\eta} - (c^{zero})^{1-\eta}}{c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}}\right)$ is always positive but less than 1 if $c_{1\mathrm{B}} < c_{tr}$, and greater than 1 if $c_{1\mathrm{B}} > c_{tr}$. Hence the logarithm of this term is negative if $c_{1\mathrm{B}} < c_{tr}$, and positive if $c_{1\mathrm{B}} > c_{tr}$. Since all other terms in the formula to the right of ΔC_{tr} are positive, we have that $\frac{\partial SCC^{NP}}{\partial \gamma}$ is sure to be negative if and only if per capita consumption in the normalization region at time 1 is less than per capita consumption in every time/region pair that experiences a climate impact. In the case of $\eta = 1$, i.e., $u(c) = \log c$, the expression $c^{1-\eta}$ in the equation above is replaced by log(c) and the same result about the sign of $\frac{\partial SCC^{NP}}{\partial \gamma}$ holds true.

$$\frac{\partial SCC^{NP}}{\partial c^{zero}} = \sum_{t=1}^{T}\sum_{r=1}^{R} \Delta C_{tr} \left(\frac{c_{1B}}{c_{tr}}\right)^{\eta} \gamma \left[\frac{c_{1B}{}^{1-\eta} - (c^{zero})^{1-\eta}}{c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}}\right]^{\gamma-1} \frac{\left(c_{tr}{}^{1-\eta} - c_{1B}{}^{1-\eta}\right)(\eta-1)(c^{zero})^{-\eta}}{[c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}]^{2}}$$

, assuming $\eta \neq 1$.

Note that every term in the summation to the right of ΔC_{tr} is always positive, except the last. The last is negative if $c_{tr} > c_{1B}$ and positive if $c_{tr} < c_{1B}$. Thus, we have a similar result as for $\frac{\partial SCC^{NP}}{\partial \gamma}$, namely that $\frac{\partial SCC^{NP}}{\partial c^{zero}}$ is unambiguously negative iff per capita consumption in the normalization region at time 1 is less than per capita consumption in every time/region pair that experiences a climate impact. This also holds true for $\eta = 1$ (not shown).

$\frac{\partial SCC^{NP}}{\partial \eta}$ presents a more complicated case. Let's use Z as an abbreviation for $\left[\frac{c_{1B}{}^{1-\eta} - (c^{zero})^{1-\eta}}{c_{tr}{}^{1-\eta} - (c^{zero})^{1-\eta}}\right]$.

$$\frac{\partial SCC^{NP}}{\partial \eta} = \sum_{t=1}^{T}\sum_{r=1}^{R} \Delta C_{tr} \left(\frac{c_{1B}}{c_{tr}}\right)^{\eta} \left[\gamma Z^{1-\gamma} \frac{\partial Z}{\partial \eta} + Z^{\gamma} \log\left(\frac{c_{1B}}{c_{tr}}\right)\right]$$

for $\eta \neq 1$.

Note that if $c_{1B} < c_{tr}$, the log of the ratio is negative, but $\frac{\partial Z}{\partial \eta}$ can be positive. Thus the sign of $\frac{\partial SCC^{NP}}{\partial \eta}$ is ambiguous even if per capita consumption in the normalization region is less than per capita consumption in every time/region pair that experiences a climate impact($\Delta C_{tr} > 0$).

An example will illustrate the ambiguity of the effect of η on SCC^{NP}. Assume for instance T=2, R=1, ΔC_{tr}=1, c^{zero}=1, γ =2, c_{1B}=2 and c_{tr} =4 so that the SCC formula above for SCC^{NP} simplifies to $SCC^{NP} = (\frac{2^{1-\eta}-1}{4^{1-\eta}-1})^{2}(\frac{1}{2})^{\eta} = \frac{2^{\eta}}{(2+2^{\eta})^{2}}$; it is then easy to see that this formula increases with η until $\eta = 1$ and then decreases with η.

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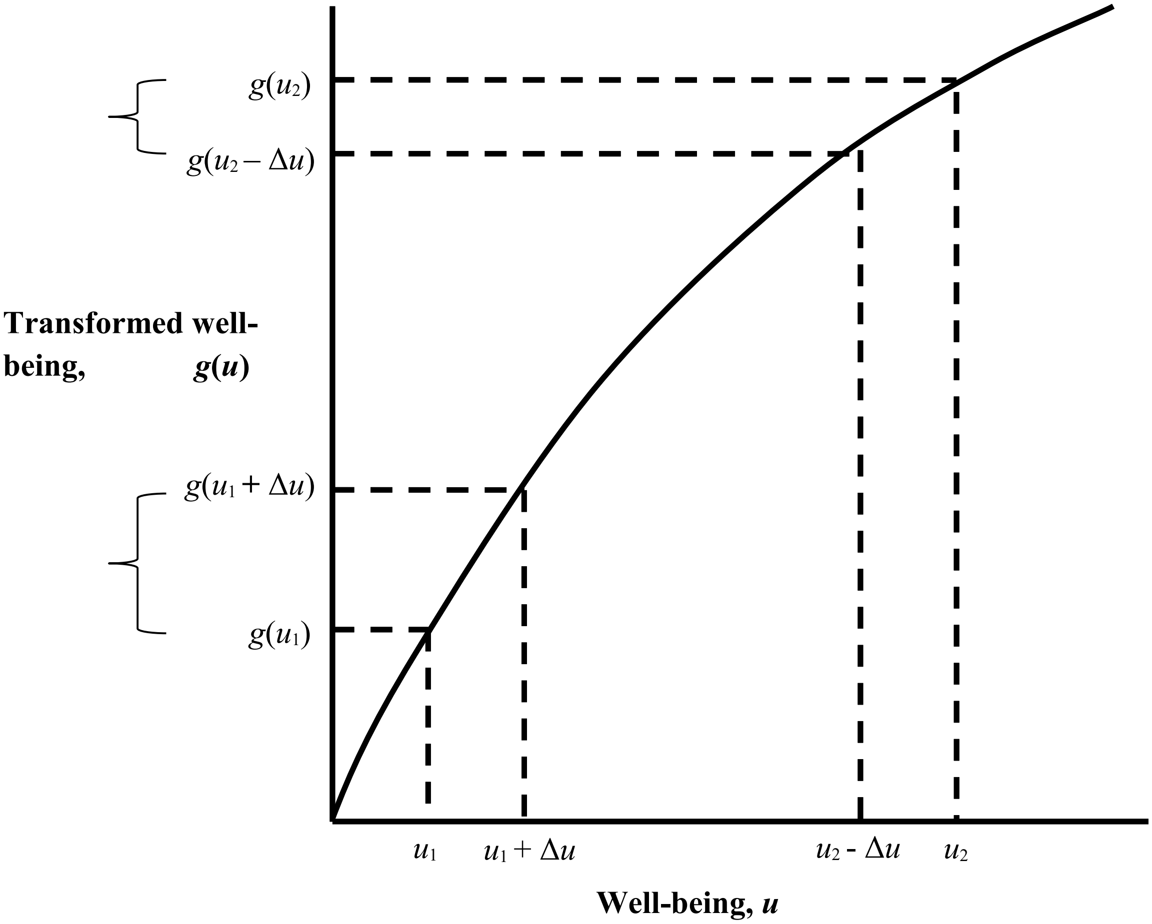
AUTHOR CONTRIBUTIONS

All authors contributed equally to developing the analytic framework, interpreting results and drafting the text. D.A. wrote code to calculate SCC values in RICE, and G.G. prepared the figures.

COMPETING FINANCIAL INTERESTS

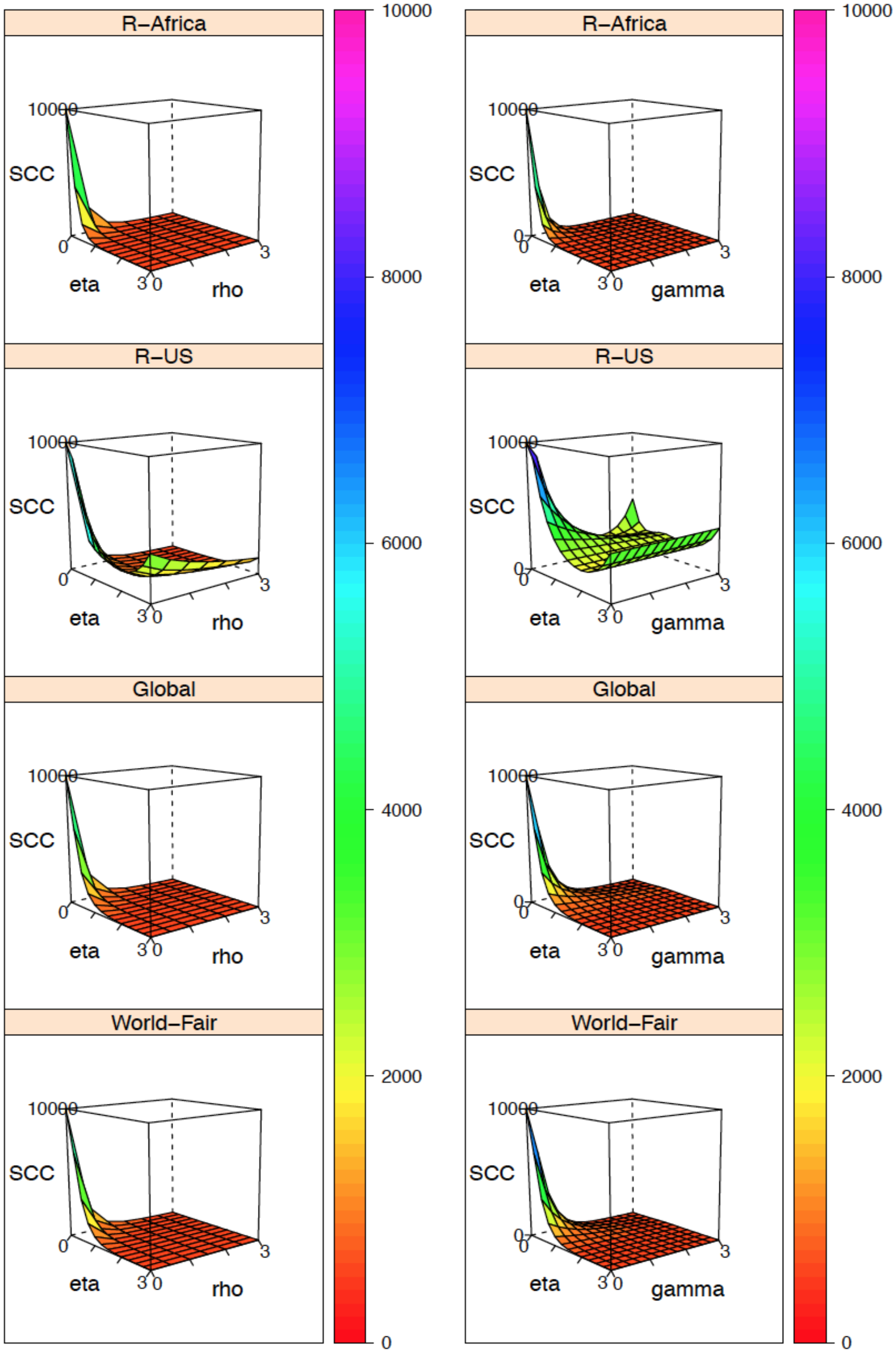
The authors declare no competing financial interests.

FIGURES Figure 1



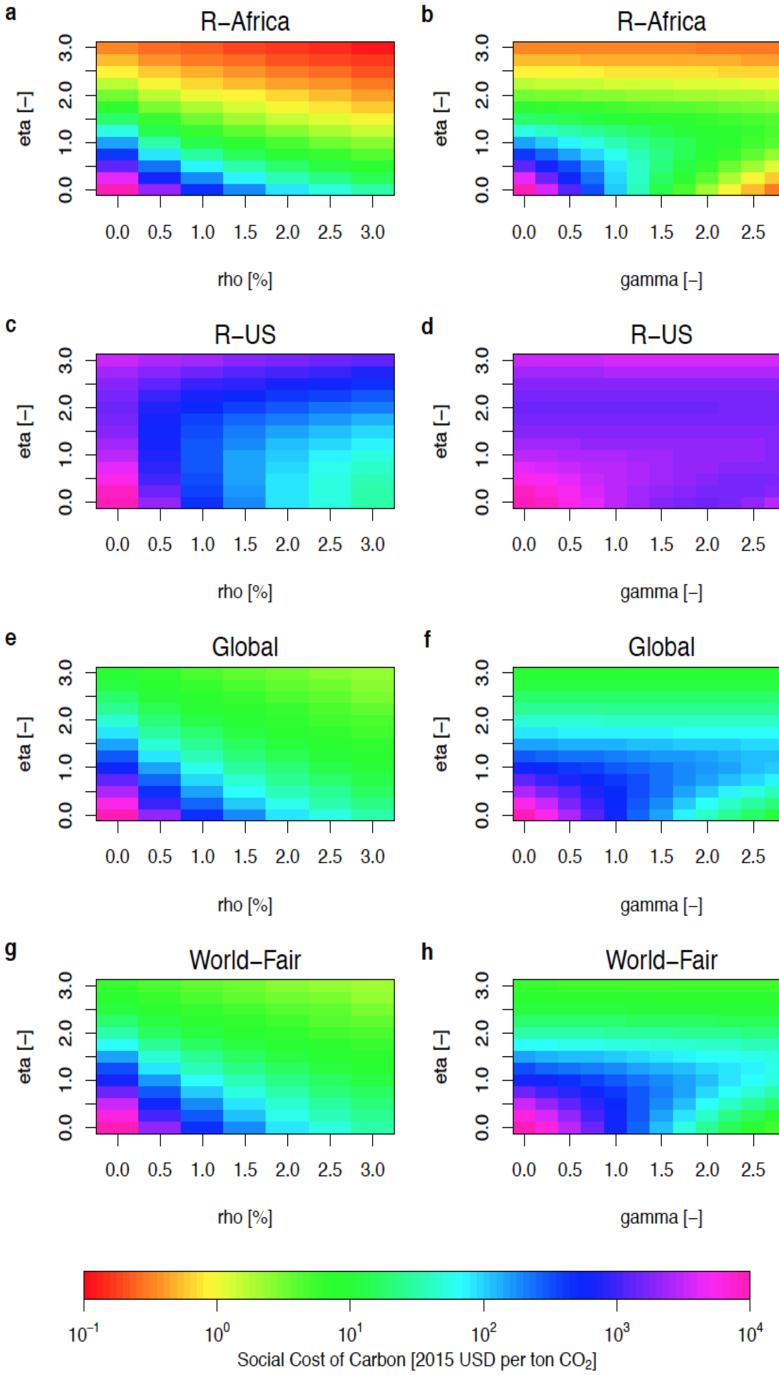
Transformed utility function $g(u)$. The prioritarian SWF sums individual well-being numbers transformed by an increasing, concave function $g(.)$. This graph shows how the effect of that transformation is to give greater weight to well-being changes affecting worse-off individuals. Consider two individuals, one at a lower well-being level u_1, the second at a higher well-being level u_2. Because the g(.) function is concave, a change in the first individual's well-being by amount Δu has a bigger impact on her *g*-transformed well-being than a change in the second individual's well-being by the same amount Δu. This also means that a pure transfer of well-being of Δu from the second individual to the first increases the value of the prioritarian SWF, i.e., the sum of *g*-transformed well-being numbers.

Figure 2



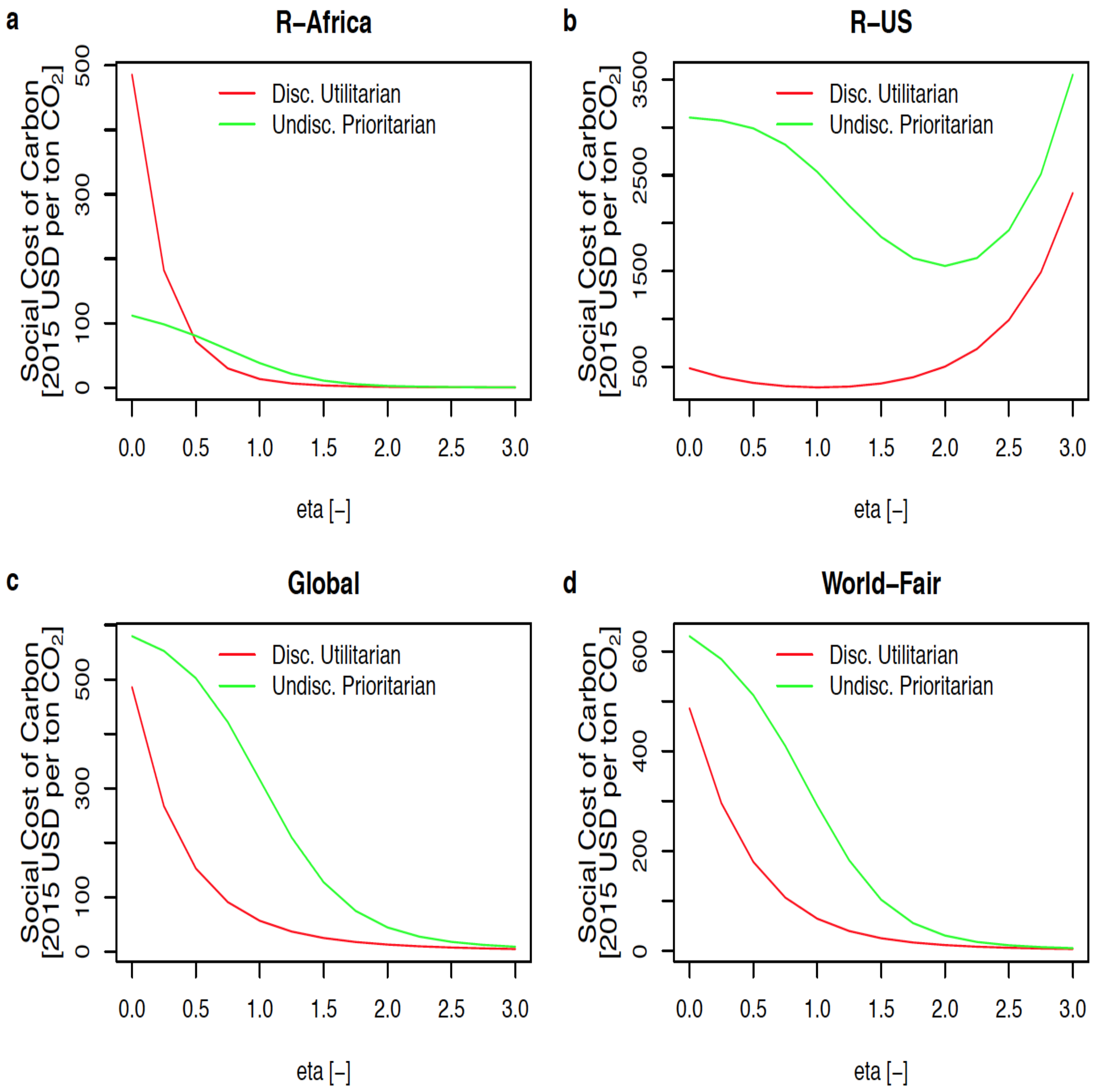
SCC^{DU} and SCC^{NP} for different normalization regions as a function of η, ρ, and γ: Wireframes. The left panel displays the discounted-utilitarian SCC (SCC^{DU}), as a function of η (eta) and ρ (rho), for the normalization regions Africa and the US, as well as the Global and World-Fair SCC^{DU} values. The right panel displays the nondiscounted prioritarian SCC (SCC^{NP}), as a function of η (eta) and γ (gamma), with c^{zero} at the central value of 500—again for the normalization regions Africa and the US, as well as Global and World-Fair. All results are in 2015 USD. Values above $10,000 are truncated to $10,000.

Figure 3



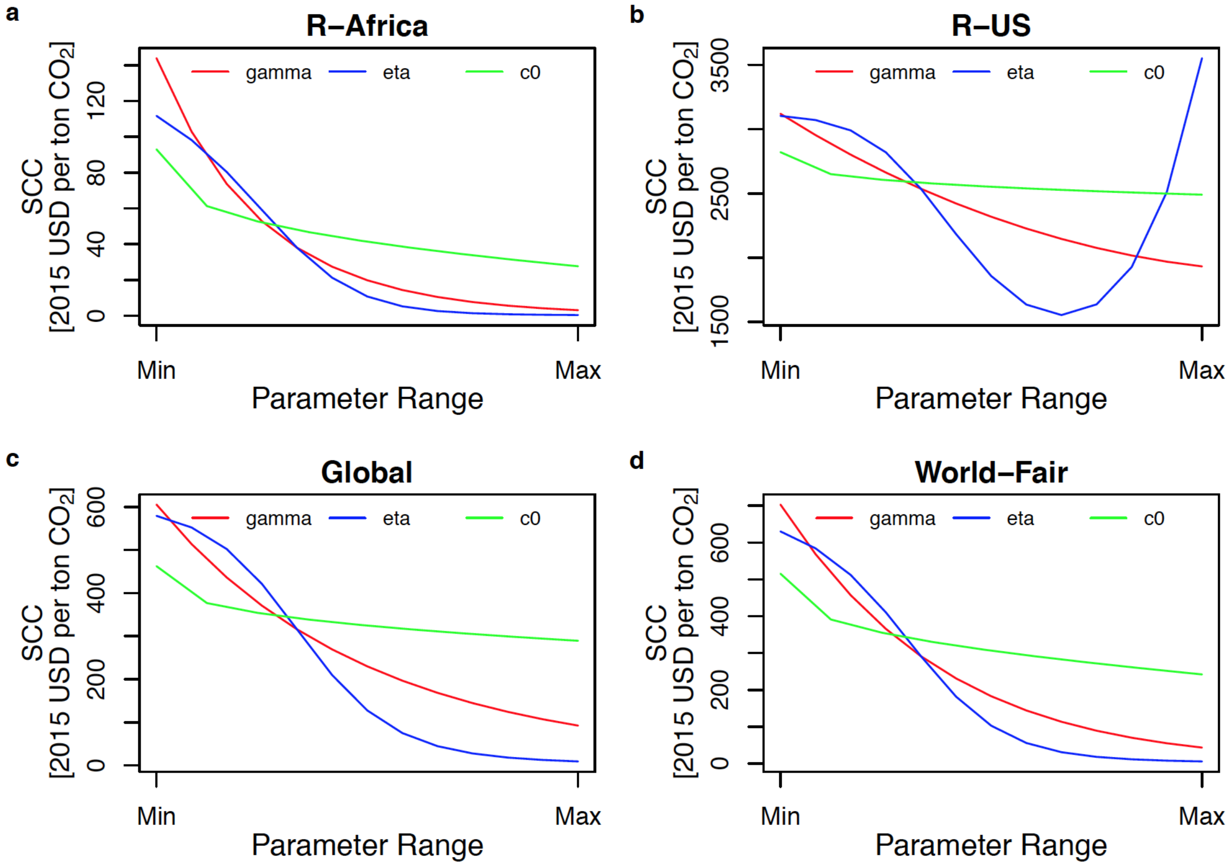
SCC^{DU} and SCC^{NP} for different normalization regions as a function of η, ρ, and γ: Heatmaps. This figure displays the same information as Figure 2, but using "heatmaps" with the colors corresponding to ranges of the value of the SCC as displayed in the rectangle at the bottom of the figure. The "heatmap" format clearly illustrates the comparative effect of γ (gamma) on SCC^{NP}, as compared to the effect of ρ (rho) on SCC^{DU}, for a common value of η (eta).

Figure 4



The magnitude of SCC^{DU} *and* SCC^{NP} *at central parameter values*. Each of the four panels contains two line graphs: one showing the effect of η (eta) on the discounted utilitarian SCC (SCC^{DU}), with ρ held at the central value of 1%; the second showing the effect of η (eta) on the non-discounted prioritarian SCC (SCC^{NP}), with γ (gamma) held at the central value of 1 and c^{zero} at the central value of 500. The four panels display this information for the normalization regions Africa and US, as well as for the Global and World-Fair calculations. All results are in 2015 USD.

Figure 5



Sensitivity analysis for the parameters of SCC^{NP}. Each of the four panels contains three line graphs. Each line displays the value of SCC^{NP} as a function of *one* of its three parameters—γ (gamma), η (eta), and c^{zero}—across the entire range of values for that parameter, with the other two parameters held at central values. The range of γ is (0, 3), with a central value of 1; the range of η is (0, 3), with a central value of 1; the range of c^{zero} is from \$1 to \$828.25, with a central value of \$500. The four panels display this information for the normalization regions Africa and US, as well as for the Global and World-Fair calculations. All results are in 2015 USD.