PRIORITY FOR THE WORSE OFF AND THE SOCIAL COST OF CARBON

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ABSTRACT The social cost of carbon (SCC) is a key tool in climate policy. The SCC is the reduction in the material consumption of the current generation that has an equivalent social impact as the emission of a ton of CO_2. The SCC is calculated using a "social welfare function" (SWF): a methodology for assessing social welfare. The dominant SWF in climate policy is the discounted-utilitarian SWF. Individuals' well-being numbers (utilities) are summed, with a discount applied to later generations. This SWF has been criticized for ignoring the distribution of well-being and including an arbitrary time preference. Here, we use a "prioritarian" SWF, with no time discount, to calculate the SCC. This SWF gives extra weight ("priority") to worse off individuals. Prioritarianism is a well-developed concept in ethics and welfare economics, but has been rarely used in climate scholarship. We find substantial differences between the discounted-utilitarian and non-discounted prioritarian SCCs.

ARTICLE TEXT

Evaluating climate policy requires a method for navigating trade-offs. The most systematic such method is the "social welfare function" (SWF) approach, which is widely used both in the economic analysis of climate change[1–4] and in other areas of economics[5–8]. The SWF approach converts information about an individual's attributes (material consumption, health, longevity, environmental conditions, etc.) into a number measuring her *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. The dominant approach in scholarship on climate policy is to use a *discounted-utilitarian* SWF[3]. Its formula sums individual well-being numbers multiplied by a weighting factor which decreases over time.

Although widely used, the discounted-utilitarian SWF is controversial. Two powerful criticisms have been raised against it. First, the time-discount factor violates the ethical axiom of impartiality. Harms and benefits to the members of later generations are downweighted by virtue of the ethically arbitrary fact that these individuals come into existence later in time[4,9–17].

Second, the utilitarian SWF (with or without a time-discount factor) ignores the distribution of well-being within any given generation[18].

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 strictly increasing and concave function (see Figure 1).

[Figure 1]

The non-discounted prioritarian SWF avoids the two criticisms of utilitarianism just mentioned. This SWF lacks a time discount factor and is thus impartial between generations. Moreover, because it gives greater weight to a well-being benefit incurred by a worse-off individual, the non-discounted prioritarian SWF 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] (where prioritarianism is sometimes discussed under the heading of "generalized utilitarianism"). It is also discussed in the chapter on ethical concepts in the most recent IPCC report[30]. However, little work has been undertaken to see what a non-discounted prioritarian SWF would recommend for climate policy, and how these recommendations differ from those of discounted utilitarianism. Existing scholarship on equity and climate change (see Supplementary Information) is generally based on the discounted-utilitarian SWF.

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 material consumption 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 US government under President Obama used the SCC to calculate the climate impact of major regulations[32,36]. Specifically, we compare the discounted-utilitarian and non-discounted prioritarian SCCs with the integrated assessment model (IAM) RICE, a widely used model that can estimate the SCC and has a regional structure[37].

Utilitarianism, Prioritarianism, and the Social Cost of Carbon: Concepts and Parameters

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. Effects on non-consumption attributes (for example, health harms from global warming) are assumed to be representable by equivalent consumption changes. The prices of goods and services are converted to a single currency—for short, "dollars"—so that the unit of consumption is one dollar.

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).

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

Again following standard practice, we use a well-being function of the form $u(c) = (1-\eta)^{-1}c^{1-\eta}$ or $\log c$ for $\eta = 1$ [1,3,4,15,16,38,39]. This well-being function is defined by a parameter, η, which captures the *declining marginal utility* of consumption. We use a range of 0 to 3 for η, with 1 as the central value.

The parameter ρ represents pure time preference. We use a range of 0 to 3% for ρ, with 1% as the central value.

The non-discounted prioritarian SWF is denoted W^{NP} and uses equation (2).

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

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

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 $g(u^*) = (1-\gamma)^{-1}(u^*)^{1-\gamma}$ or $\log u^*$ in the special case of $\gamma = 1$. The parameter γ is a pure ethical parameter. It 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. In our analysis, we use a range of 0 to 3 for γ, with 1 as our central value.

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 well-being function above and then rescaling by setting $u^*(c) = u(c) - u(c^{zero})$ [7,19]. 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. Within this range, the choice of c^{zero} is, again, an ethical matter. 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[40]

See Methods for a fuller discussion of the parameters η, ρ, γ, and c^{zero}, and of the role of ethical judgment in specifying them.

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[41]. 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 (SCC^{DU}); by combining it, instead, with equation (2), we arrive at the non-discounted prioritarian SCC (SCC^{NP}).

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

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.

How would a globally impartial decisionmaker (one who does not differentially weight the interests of persons because of their regional location) use an SCC that depends on normalization region to evaluate carbon policy? In order to do so, the decisionmaker needs to take account of the region-by-region *incidence* of the current consumption losses resulting from the policy. Imagine that a policy will reduce emissions by ΔE tons, and will reduce total consumption by the current generation by amount ΔC. If that consumption loss is borne entirely by individuals in region *B*, then the policy is "worth it" if ΔE multiplied by the SCC with *B* as normalization region exceeds ΔC. More generally, if the consumption loss is spread among the regions (with each region *r* incurring some fraction π_r of the total loss ΔC), then the policy is "worth it" if ΔE multiplied by a blended SCC (with a denominator equaling the weighted average marginal social welfare impact of consumption, with the π_r as weighting factors) exceeds ΔC. See equation (3*) below.

The supposition of a globally impartial decisionmaker is an ethical idealization. Actual policymakers in a given country might depart quite substantially from this ethical ideal and downweight both the benefits and the costs of carbon reduction that accrue to noncitizens. See Methods for a fuller discussion of the use of a globally impartial perspective in calculating the SCC.

The Discounted-Utilitarian and Non-discounted Prioritarian SCC

We illustrate the SCC with three normalizations: the US, Africa, and a "World-Fair" normalization which is a blend of all the regions. 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 consumption in the normalization region. 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.

In general, the SCC (be it utilitarian or prioritarian) can be calculated relative to a “business as usual” scenario, or on the assumption that emissions and economic growth have been chosen to optimize the SWF. We calculate a “business as usual” SCC. Our results are in US dollars (2015 price levels) per ton of CO_2 emissions.

See Supplementary Information for details of our calculation of the SCC.

Recall that η is the parameter of the well-being function that determines the rate at which the marginal utility of consumption declines, and that is used in both the discounted-utilitarian and non-discounted prioritarian SWF. The parameter 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 normalizations US, Africa, and World-Fair, as well as the Global calculation, as a function of η and ρ.

[Figures 2 and 3]

The right column of Figure 2 shows SCC^{NP} for those normalizations 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 three-dimensional graphs. Figure 3 displays the very same information, but in two-dimensional “contour” plots. We truncate extreme values of SCC (above \$10,000) 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 contains one-dimensional sensitivity plots showing how SCC^{DU} and SCC^{NP} vary with η (given central values of the other parameters), for the three normalizations and for Global.

[Figure 4]

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 marginal-utility parameter η (at or near zero), the SCC^{DU} with $\rho = 0$ takes on extreme values for all normalizations and Global. Holding constant η, increasing ρ reduces the SCC^{DU}. This is consistent with an argument sometimes made in defense of positive time preference—that zero time preference can require unreasonably large sacrifices from the present generation, to the extent their activities have effects on many future generations[1,39,42].

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 reaches extreme levels with low values of η *if* γ is set to zero, but these levels diminish—*without introducing a time preference*—as γ is increased moderately. Even with the marginal-utility parameter η set equal to zero (constant rather than declining marginal utility), a very moderate level of the priority parameter $\gamma \geq 0.2$ for all normalizations and Global suffices to avoid an extreme SCC^{NP}. 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. However, one might wonder whether ρ and γ are, for practical purposes, roughly equivalent.

Figure 3 demonstrates that this is not the case. 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.

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 Supplementary Information.

(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 $\gamma = 1$ and $c^{zero} = \$500$, and SCC^{DU} with $\rho = 1\%$, each calculated as a function of the common parameter η. In all cases, with η at or above 0.5, SCC^{NP} is larger than SCC^{DU}—although as η increases, the ratio between SCC^{NP} and SCC^{DU} approaches unity. (With Africa as the normalization region, SCC^{DU} exceeds SCC^{NP} for low η).

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

Figure 4 illustrates the comparison of $\mathrm{SCC}^{\mathrm{NP}}$ and $\mathrm{SCC}^{\mathrm{DU}}$ given a judgment about the plausible central values of the parameters γ, c^{zero} and ρ. A different judgment would yield a different comparison.

In Figure 4, the magnitude of the $\mathrm{SCC}^{\mathrm{NP}}$ values for the US normalization region, which lie in the range \$1600 to \$3600, is—perhaps—surprising. Note, however, that $\mathrm{SCC}^{\mathrm{DU}}$-US values are also quite large, and that the choice of the 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 $\mathrm{SCC}^{\mathrm{DU}}$ and $\mathrm{SCC}^{\mathrm{NP}}$. 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 $\mathrm{SCC}^{\mathrm{NP}}$ and $\mathrm{SCC}^{\mathrm{DU}}$ are much lower than the regionally disaggregated estimates with the US as normalization region.

(4) <u>The marginal utility of consumption (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</u>. Our discussion 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. See Supplementary Information for details.

Analytically, the effect of γ on $\mathrm{SCC}^{\mathrm{NP}}$ is complex. If the normalization region (as with Africa) is poorer at present than all future regions, $\mathrm{SCC}^{\mathrm{NP}}$ will decrease as γ increases. (The intuition is that, with a poorer normalization region, a greater degree of priority for the worse off means greater weight for consumption losses in that region, as compared with consumption losses caused by carbon emissions in all regions in the future—and thus a lower $\mathrm{SCC}^{\mathrm{NP}}$.) But $\mathrm{SCC}^{\mathrm{NP}}$ can, in principle, decrease or increase with γ with a normalization region that is not poorer than all future regions (US) or a composite normalization (World-Fair).

Similar points hold true of c^{zero}. The effect of η on $\mathrm{SCC}^{\mathrm{NP}}$ is yet more complex: even with a normalization region that is worse off than future regions, $\mathrm{SCC}^{\mathrm{NP}}$ might decrease or increase with η. Some of these non-monotonicities can be observed in the right panels of Figures 3 and 4.

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

[Figure 5]

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

The effect of the priority parameter γ on $\mathrm{SCC}^{\mathrm{NP}}$ will become small as c^{zero} approaches its lower bound (0), if $\eta \geq 1$. However, in the central case displayed in Figure 5, with c^{zero} =\$500, γ has a substantial impact on $\mathrm{SCC}^{\mathrm{NP}}$.

Conclusion

We hope that this analysis will help prompt future research on the implications of prioritarianism for climate policy. The RICE model assumes that all regions experience economic growth. Future work should consider the possibility that climate impacts might forestall growth in poorer regions. Nor does our analysis take account of income inequality within regions[43,44]. Finally, the RICE model is deterministic; an incremental ton of emissions produces determinate consumption losses in future time-region pairs. Future research should take account of the probabilistic nature of carbon impacts—examining the combined implications of inequality and uncertainty.

Notwithstanding these caveats, we believe that our analysis sheds new light on the SCC, and demonstrates that prioritarianism can usefully enrich the normative evaluation of climate policy, by broadening a scholarly discourse that—until now—has been dominated by the discounted-utilitarian approach.

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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.

DATA AND CODE AVAILABILITY

The data and code to reproduce the results shown in this study will be available upon publication at https://doi.org/XX.XXXX/zenodo.XXXXXX.

COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

METHODS

Specifying the Parameters of an SWF: Normative or Descriptive?

A major debate among climate scholars concerns whether the specification of an SWF is "descriptive" or "normative"[15,16,42,45,46]. The former approach seeks to avoid ethical judgments, while the latter frankly incorporates such judgments. Here we adopt the normative approach. Although some SWF parameters may be identifiable from empirical observation (see below, discussing the parameter η), 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[47]—such as utilitarianism or prioritarianism.

The η Parameter

Recall that for both the DU and NP SWFs, we are using a well-being function of the form $u(c) = (1-\eta)^{-1}c^{1-\eta}$ or log c for $\eta = 1$. η reflects the marginal utility of consumption—the change in well-being, per unit of consumption. If η is zero, marginal utility is constant: an increment in an individual's consumption from c to $c + \Delta c$ produces the same increase in well-being regardless of the value of c. If η is positive, marginal utility is decreasing: a given increment Δc produces a smaller change in well-being as c gets larger. As η increases, marginal utility decreases at a faster rate.

As already mentioned, this well-being function is quite standard in climate scholarship. This literature generally uses values in the [0.5, 3] range[1,3,4,16,32,39,45]. A recent review finds 1 to be a common value[3], and indeed is the value adopted in the Stern review[4]. Nordhaus in more recent work adopts $\eta = 2$ [1], although earlier adopted $\eta = 1$ [48].

One way to calibrate η is to look to individual risk aversion with respect to consumption gambles[49]. This approach rests upon the premise ("Bernoulli") that the ranking of consumption gambles is risk neutral in well-being itself[50,51]. Assume that a decisionmaker believes that a consumption level of c would produce a certain level of well-being for some individual; that increasing her consumption by Δc would increase her well-being by Δu; and that decreasing her consumption by Δc^* would decrease her well-being by the very same amount (Δu). Then the Bernoulli premise stipulates that the decisionmaker, if concerned about the individual's well-being, should be indifferent between giving her c and giving her a 50-50 gamble between ($c + \Delta c$) and ($c - \Delta c^*$). This creates a fundamental linkage between risk aversion and marginal utility.

Although other methodologies are also plausible[52], it is routine in welfare economics to use individual risk aversion in consumption gambles as the basis for determining the marginal utility parameter η[53–56]. We henceforth refer to the function $u(c) = (1-\eta)^{-1} c^{1-\eta}$ as the "constant relative risk aversion" (CRRA) function, the standard terminology in the risk-aversion literature. Recent empirical studies on investment choices find support for the CRRA functional form[57,58]. Estimated values for η are often in the range between 0.5 and 3 [59–62]—consistent with the range used by climate economists. Quiggin suggests that "in discussions focused on risk, the most common single parametric choice is η =1".[63]

A more nuanced well-being function would allow for heterogeneous preferences[19], with an individual's well-being a function both of her consumption and an individual-specific level of η; but this has not been implemented in climate economics and is rarely done in SWF scholarship more generally[5].

The ρ Parameter of the DU SWF

The parameter ρ represents pure time preference. Like γ and c^{zero} below, this is a normative rather than descriptive parameter (albeit one that conflicts with the ethical axiom of impartiality) in the sense that, to specify it, one needs to make a normative judgment about the appropriate degree of downweighting of future well-being. Stern advocates ρ = 0 (except for extinction risk)[4,45]; Nordhaus [1,42] sets ρ = 1.5%; Weitzman suggests ρ = 2% [39]. In a survey of 197 experts on social discounting, Drupp *et al.*[46] 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 γ and c^{zero} parameters of the NP SWF

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 $u(c) = (1-\eta)^{-1} c^{1-\eta}$ (log *c* for η = 1) 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

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

$$\Leftrightarrow$$

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

By contrast, the NP SWF in the generic form of summing a strictly increasing, concave function of individual well-being is *not* invariant to a positive affine transformation of the well-being function. Let *g*(.) be any strictly 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:

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

$$\Leftrightarrow$$

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

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 an important argument *for* the Atkinson *g*(.) function. 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 seems 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.

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

for $\gamma = 1$

For a given individual i, the marginal ethical impact of well-being, $\frac{\partial w}{\partial u_i^*}$, equals $(u_i^*)^{-\gamma}$ or, equivalently, $[u(c_i) - u(c^{zero})]^{-\gamma}$. The marginal ethical impact of consumption, $\frac{\partial w}{\partial u_i^*}\frac{du_i^*}{dc_i}$, equals $(u_i^*)^{-\gamma}\frac{du_i^*}{dc_i}$ 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 strictly increasing and strictly 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 main 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 $\left(\dfrac{u(c_j) - u(c^{zero})}{u(c_i) - u(c^{zero})} \right)^{\gamma} \dfrac{u'(c_i)}{u'(c_j)}$. 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.

Some scholarship in welfare economics tackles the problem of valuing changes in the size of the population. Here, the so-called "neutral level" of well-being (a life that is neither better nor worse for the individual than non-existence) and the "critical level" (a life that is just good enough to be worth creating, as an ethical matter) are key topics for discussion[29,65–66]. Conceptually, c^{zero} (the point of absolute priority) is different from both the neutral and critical levels; it can, but need not, be set equal to one or the other[19].

Here we assume a fixed (exogenous) population, and postpone for future research the use of a prioritarian SWF to evaluate climate policies that change the size of the population. The neutral and critical levels are, therefore, not parameters we need to specify here

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 $\gamma = 1$ the maximum ethically acceptable leakage rate is 50%. With $\gamma = 2$ it becomes 75%, and with $\gamma = 3$ it is 88%. If the ratio increases to $K = 3$, then these maximum acceptable rates become, respectively, 67% ($\gamma = 1$), 89% (2), and 96% (3).

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

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

It bears reminder that the NP SWF is a tool for ethical decisionmaking. The "leaky transfer" experiments just discussed therefore ask us to consider leaky transfers of well-being or consumption assuming impartiality between the better- and worse off individuals. The answers to such thought experiments will change if the deliberator feels "closer" (in space, time, or some other sense) to one of the individuals, and is thereby prompted to depart from impartiality.

For citations to surveys estimating respondents' judgments of γ or related work, see Adler (pp. 397-399)[7].

Calculating SCC using a Globally Impartial SWF

The ethical ideal of impartiality is formally captured, in the SWF literature, in an "anonymity" axiom. Permutations of well-being numbers should leave the value of the SWF unchanged[7]. Both the DU and NP SWFs are "globally" impartial, in the sense that permutations of well-being among individuals in different regions at the same time do not change the value of the SWF. In other words, the SWFs do not include regional weighting factors. The NP SWF is fully impartial (temporally *and* globally), while the DU SWF is not temporally impartial, because it includes a time-discount factor (ρ).

Both SCC^{DU} and SCC^{NP}, in turn, reflect the global impartiality of the underlying SWF. SCC^{DU} or SCC^{NP} for a given normalization region is the change in the present consumption of that region which has the very same impact on social welfare as a ton of CO_2 emissions —*as those social-welfare impacts are calculated using the globally impartial SWF*, namely W^{DU} or W^{NP}.

Global impartiality may well recommend policies that actual policymakers in a given country, who may be partial to local interests, find politically infeasible. First, W^{DU} and W^{NP} both may recommend the expenditure of large sums of money on emissions mitigation. For example, as shown in Figure 4, SCC^{DU} with a US normalization lies in the range \$300 to \$2300, while SCC^{NP} ranges from \$1600 to \$3600. It seems naïve to think that current US policymakers would actually spend these sums to mitigate a ton of CO_2.

Second, W^{DU} and W^{NP} both may recommend transfers of consumption from richer to poorer regions that are politically infeasible. Both SWFs are such that the marginal social welfare impact of consumption is decreasing. If region L has lower per capita consumption than region B, a given change ΔC to the total consumption of region L has a greater effect on social welfare than the same change to the total consumption of region B. (For W^{DU}, this occurs if $\eta > 0$, so that consumption has diminishing marginal utility; for W^{NP} the effect is compounded by priority for the worse off with $\gamma > 0$). Thus a transfer of ΔC from a richer to a poorer region, without loss and any other effect beyond the transfer, always increases social welfare.

To be sure, a sophisticated social-welfare analysis of international transfers using W^{DU} or W^{NP} would need to consider the disincentive effects—with respect to income-generating activities in richer countries—of large transfers, and some loss rate with respect to transferred funds because of administrative costs, corruption, etc. Still, even accounting for disincentives and loss, such an analysis might well recommend transfers much larger than are politically feasible for policymakers in the transferor countries.

Some scholarship in climate economics uses so-called "Negishi" weights to counteract regional differences in the marginal social welfare impact of consumption[67]. Such weights are designed to ensure that the SWF will not recommend international transfers of consumption, which are judged to be politically infeasible. But by including Negishi weights, the SWF departs from global impartiality. Our approach, instead, is to construct SWFs and derive SCCs that reflect the ethical ideal of the equal weighing of individuals regardless of region—leaving it to policymakers to decide for themselves how closely to conform to the ideal.

Finally, it should be noted that a sensible decisionmaker (be it a globally impartial decisionmaker or one constrained by political feasibility) would take into consideration a *range* of policies for increasing social welfare—carbon mitigation, international transfers, or mixed policies including both as components. As noted in the main text, the SCC with region B as normalization (SCC_B) is such that reducing emissions by ΔE tons has the same social-welfare impact as increasing consumption in region B by $(\text{SCC}_B)\Delta E$ dollars. This means, specifically, that a policy of reducing emissions by ΔE tons and paying for that mitigation by reducing consumption in region B by ΔC increases social welfare—*as compared to the alternative of governmental inaction, whereby both emissions and consumption levels are left undisturbed*—if $\Delta C < (\text{SCC}_B)\Delta E$. However, it might be the case that a yet larger increase in social welfare could be generated by leaving carbon emission as is and instead transferring ΔC dollars (with some degree of loss or disincentive effect) from region B to a poorer region.

Consider that the ratio between the marginal social welfare impact of consumption in a second region, L, and the marginal social welfare impact of consumption in region B is just $\text{SCC}_B/\text{SCC}_L$. Assume that L has lower per capita consumption than B and that a globally impartial decisionmaker in region B has the three-way choice between inaction; expending ΔC in region B consumption in order to reduce emissions by ΔE tons; or leaving emissions unchanged but transferring ΔC (for simplicity, without loss or disincentive effect) to region L. Then the third, transfer policy increases social welfare as compared to inaction. In turn, the emissions reduction policy produces a yet larger increase in social welfare if emissions reduction is sufficiently "cheap," specifically if $(\mathrm{SCC}_B/\mathrm{SCC}_L)\ \Delta C < \mathrm{SCC}_B(\Delta E)$. This last equation is, in turn equivalent to: $\Delta C < (\mathrm{SCC}_L)\Delta E$. Emissions reduction is preferred by the SWF to transfer if the social-welfare value of emissions reduction, expressed now in equivalent units of region L consumption, is greater than the social-welfare value of the transfer in terms of region L consumption, which is just ΔC.

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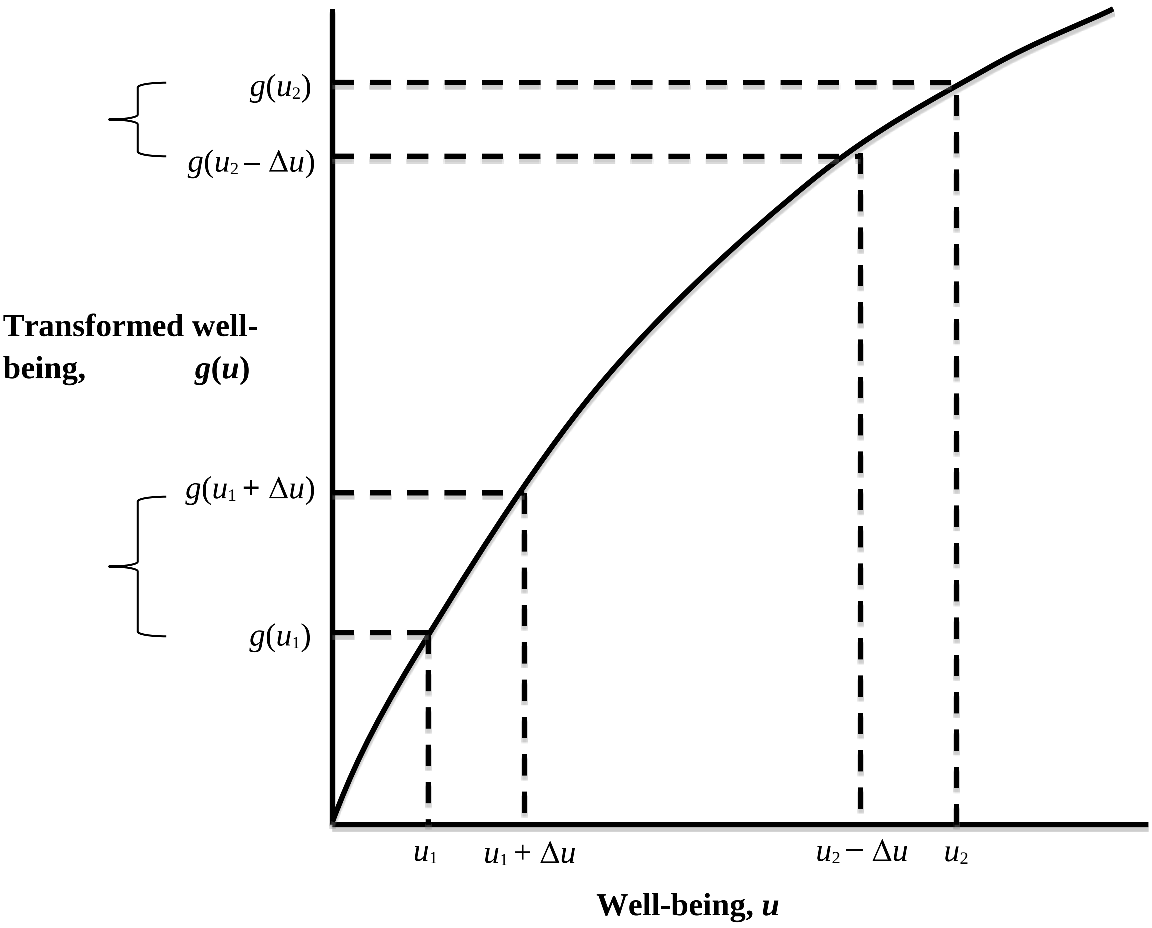
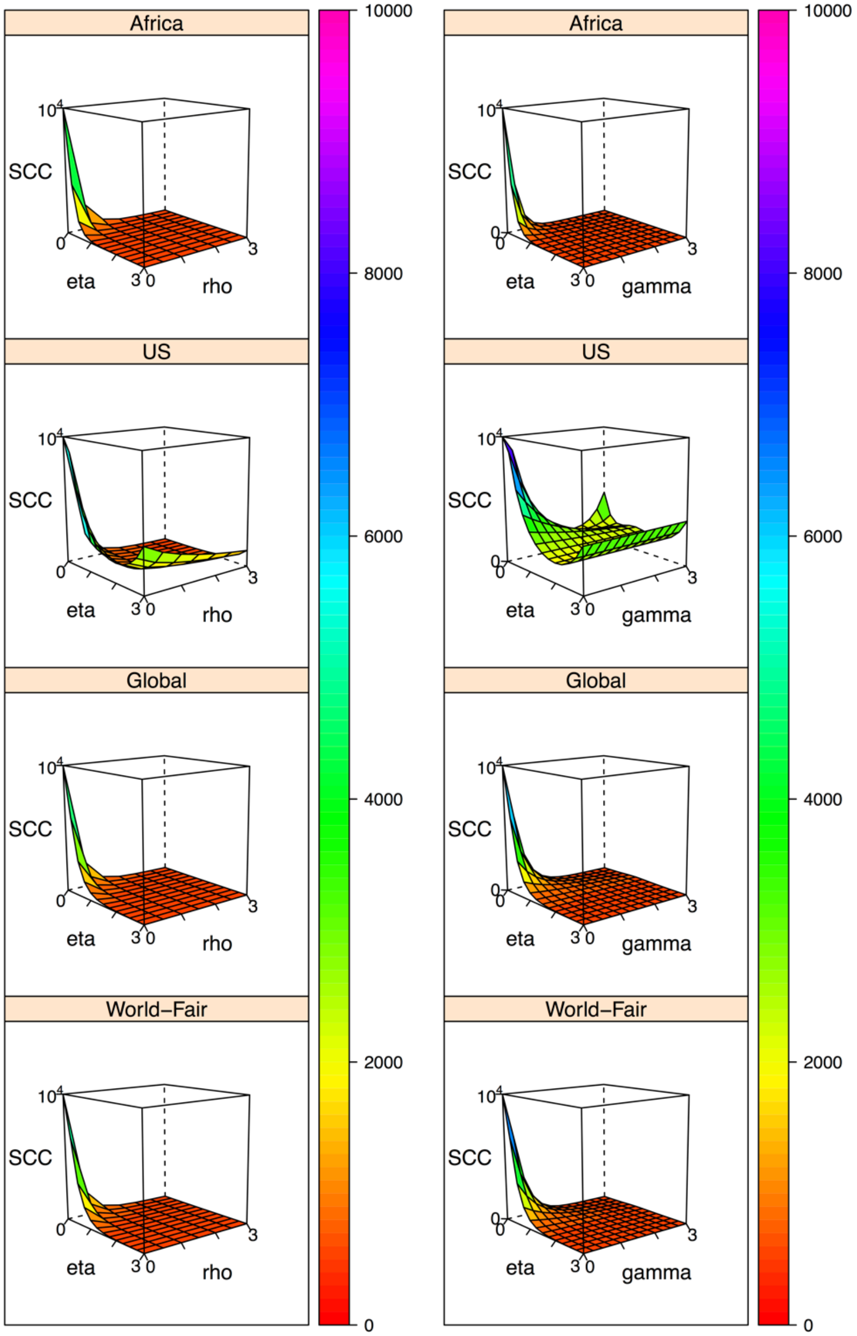
FIGURES

Figure 1



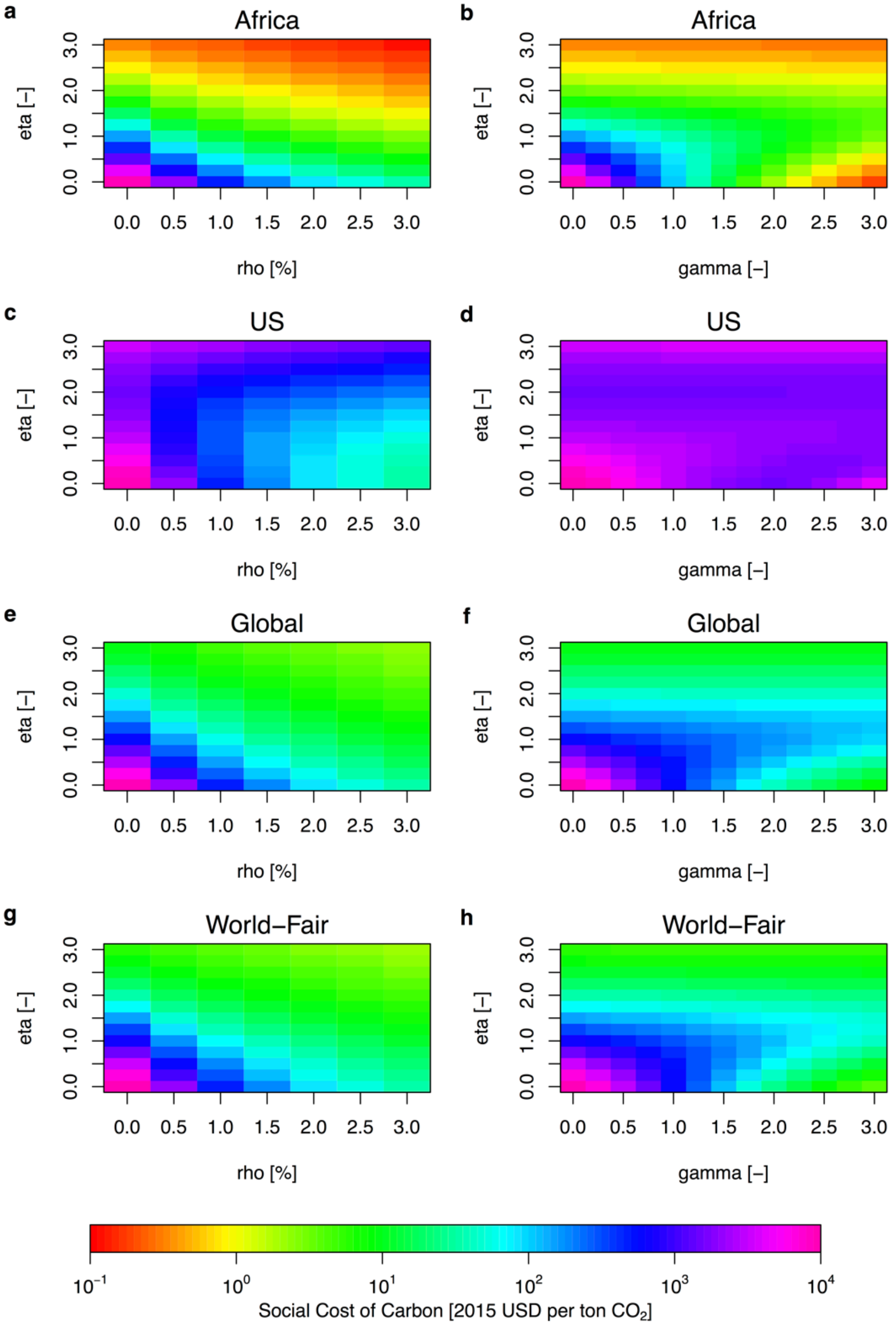
Prioritarian transformation function. The prioritarian SWF sums individual well-being numbers transformed by a strictly increasing and concave function $g(.)$. This gives greater weight to well-being changes affecting worse-off individuals. Consider two individuals, the first at well-being level u_1, the second at higher level u_2. Because $g(.)$ is strictly concave, a change in the first individual's well-being by amount Δu has a larger impact on her g-transformed well-being than a change in the second individual's well-being by the same amount Δu. Further, a pure transfer of Δu from the second individual to the first increases the value of the prioritarian SWF.

Figure 2



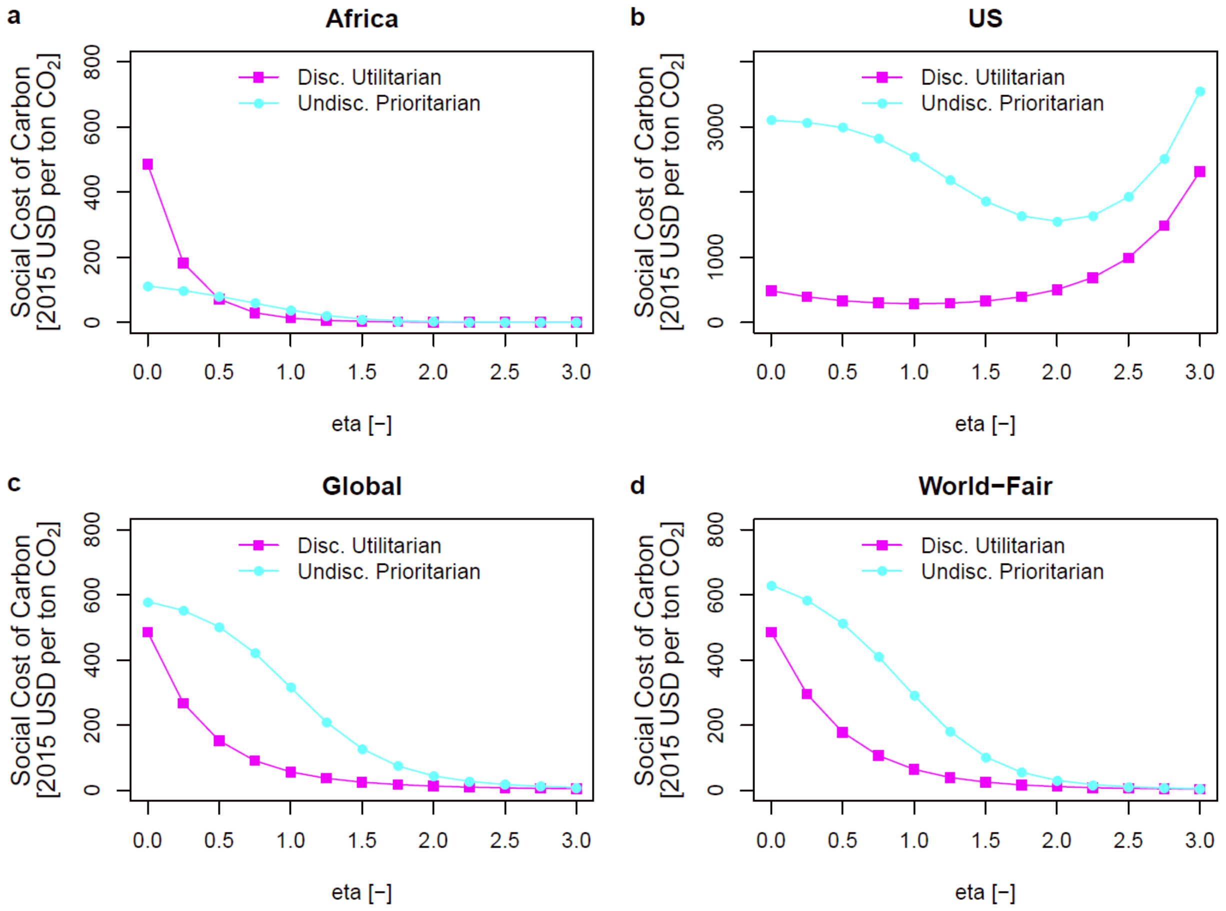
SCC^{DU} and SCC^{NP} as a function of η, ρ, and γ. The left panel displays the discounted-utilitarian SCC (SCC^{DU}), as a function of η (eta) and ρ (rho, values in %), for the three normalizations (Africa, US, and World-Fair), as well as the Global SCC^{DU}. The right panel displays the nondiscounted 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 three normalizations and also calculated on a Global basis. All results are in 2015 USD. Values above \$10,000 are truncated to \$10,000.

Figure 3



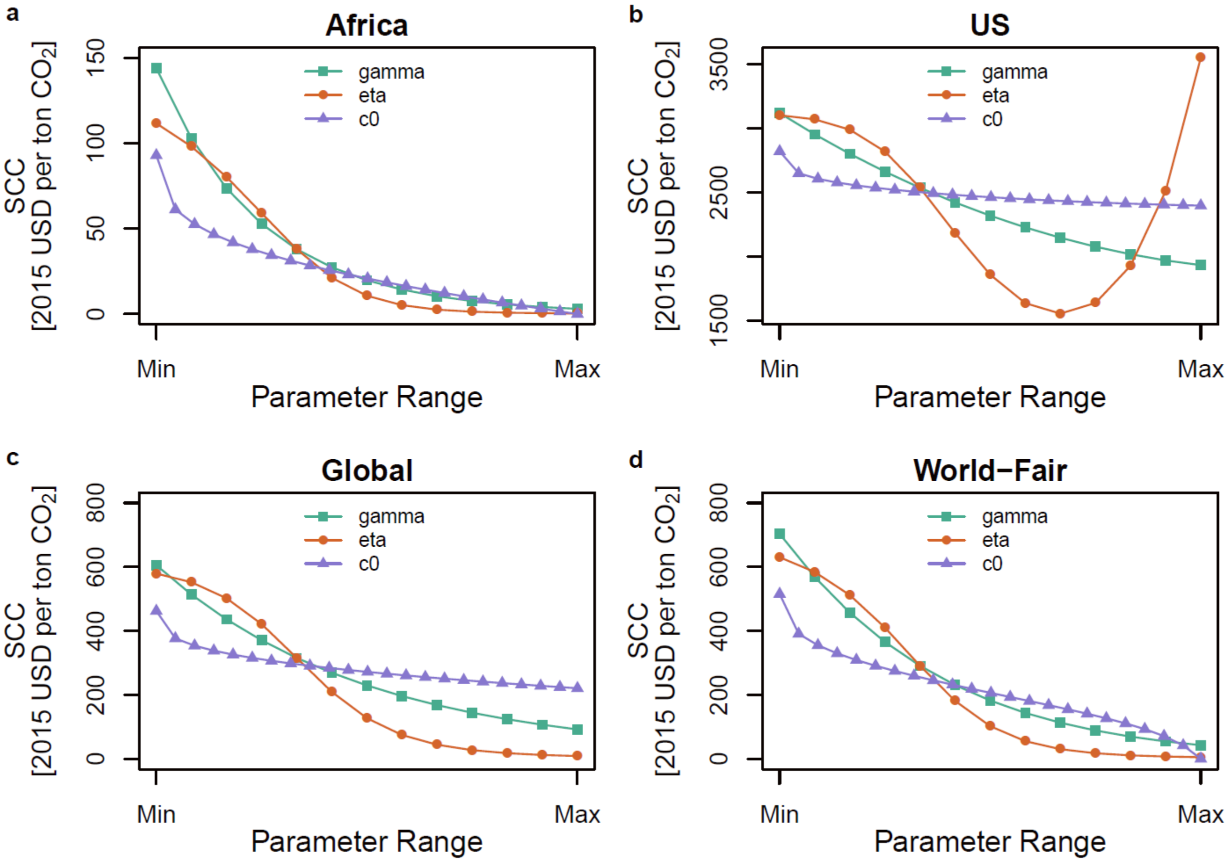
SCC^{DU} and SCC^{NP} as a function of η, ρ, and γ: Contour Plots. This figure displays the same information as Figure 2, but using contour plots with the colors corresponding to ranges of the value of the SCC as displayed in the rectangle at the bottom of the figure. This format clearly illustrates 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



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 three normalizations (Africa, US and World-Fair) and for the Global SCC calculation. All results are in 2015 USD.

Figure 5



The parameters of SCC^{NP}: Sensitivity Analysis. Each of the four panels (for the three normalizations and Global) contains three lines. Each line displays the value of SCC^{NP}, in 2015 USD, as a function of *one* of its three parameters—γ (gamma), η (eta), and c^{zero}—across the 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 ($1, $2191), with a central value of $500.