

Circumspection, reciprocity, and optimal carbon prices

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Abstract Assessments of the benefits of climate change mitigation—and thus of the appropriate stringency of greenhouse gas emissions abatement—depend upon ethical, legal, and political economic considerations. Global climate change mitigation is often represented as a repeated prisoners’ dilemma in which the net benefits of sustained global cooperation exceed the net benefits of uncooperative unilateral action for any given actor. Global cooperation can be motivated either by circumspection—a decision to account for the damages one’s own actions inflict upon others—or by the expectation of reciprocity from others. If the marginal global benefits of abatement are approximately constant in total abatement, the domestically optimal price approaches the global cooperative optimum linearly with increasing circumspection and reciprocity. Approximately constant marginal benefits are expected if climate damages are quadratic in temperature and if the airborne fraction of carbon emissions is constant. If, on the other hand, damages increase with temperature faster than quadratically or carbon sinks weaken significantly with increasing CO₂ concentrations, marginal benefits will decline with abatement. In this case, the approach to the global optimum is concave and less than full circumspection and/or reciprocity can lead to optimal domestic abatement close to the global optimum.

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1 Introduction

Regardless of whether it is implemented in the form of an explicit carbon price or more targeted policies and measures, climate change mitigation policy involves trade offs. On one side are the uncertain costs of transforming the energy system; on the other, the still more uncertain and “fat-tailed” costs of climate change itself. By explicitly balancing these tradeoffs, quantitative benefit-cost analysis (BCA) can inform decisions about the appropriate stringency of mitigation policies, but its application requires an estimate of the economic benefits of abating emissions. The social cost of carbon (SCC) provides a measure of these benefits. It is an estimate of the change in expected welfare of a representative agent resulting from a marginal emission of CO₂, normalized by the change in expected welfare resulting from a marginal decrease in consumption. In other words, it expresses the amount a representative agent should be willing to spend to obtain a marginal reduction in CO₂ emissions.

Estimates of the SCC are currently used by the U.S. government as part of BCA of proposed regulations with impacts on greenhouse gas emissions (Interagency Working Group on the Social Cost of Carbon 2010, 2013). A number of core assumptions underlie these analyses; these include scenarios of future economic growth and emissions, the near-term and long-term response of the climate to greenhouse gas forcing, the economic damages incurred as a result of different amounts of climate change, the discount factors used to weight different time periods and states of the world, and the equity weights used to value regions with different levels of consumption (Kopp and Mignone 2012; Anthoff and Tol 2010). Here, we focus on two related decisions regarding scenario selection and the inclusion of economic damages abroad. First, the existing U.S. SCC estimates utilize emissions scenarios that predominantly represent business-as-usual (BAU) pathways, with no major global mitigation actions, as opposed to benefit-cost optimal pathways. Second, the U.S. SCC damage estimates incorporate the costs of climate change not just to the United States but to the world as a whole. In other words, the U.S. estimates are measures of the *global* SCC rather than the *domestic* SCC.

Masur and Posner (2011) note that the choice of a global SCC raises normative and institutional questions. In particular: do citizens of one country have the same obligations toward foreigners as toward their fellow citizens, or should damages to foreigners be weighted less than domestic damages? And how are other nations’ abatement actions likely to depend upon one’s own choices or choices by third parties? This latter question links the two sets of earlier decisions together; if greater abatement by one country leads to increased abatement by others, a higher domestic carbon price will deflect global emissions more significantly away from BAU, thus informing the selection of an appropriate scenario.

Estimates of the SCC that exceed the domestic SCC can be motivated on one of two grounds: an ethical/legal principle we call *circumspection* or a political economic principle we call *reciprocity*. Masur and Posner’s first question relates to circumspection, and their second to reciprocity.

Circumspection (from the Latin *circumspecere*, “to look around”) refers to the inclusion of extraterritorial damages caused by one’s own actions. Circumspection might be motivated by acceptance of the “polluter pays” norm, or by the expectation of tort liability under that principle (Sachs 2008). This norm is well-established

in international law. For example, the 1972 Stockholm Declaration declares that “States have ... the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States” (United Nations 1972). In the United States, consideration of extraterritorial damage caused by federal action has been mandated for more than three decades under National Environmental Protection Act guidance (Carter 1979; Council on Environmental Quality 1997), and four decades of legal precedents have recognized the standing of foreign intervenors to challenge Environmental Impact Statements (e.g., *Wilderness Society v. Morton* 1973; *Swinomish Tribal Community v. FERC* 1980). In addition, if potential “spillover” of climate change damages between regions (for example, due to economic or national security interactions) is not explicitly incorporated into domestic damage estimates, circumspection might be used as a way to account for these effects (Kopp and Mignone 2012; Warren 2011).

Reciprocity refers to additional mitigation from other nations in response to domestic mitigation. It can be a self-interested response to mitigation by others under some payoff structures, such as a repeated prisoners’ dilemma (Barrett 2002). Assumptions about reciprocity may be implicit or explicit in policy formulation. An example of implicit reciprocity is the 2009 North American Leaders’ Declaration on Climate Change, in which heads of state committed themselves to setting and implementing “ambitious mid-term and long-term goals to reduce national and North American emissions” in the hopes of “strengthen[ing] the political momentum behind a successful outcome at the 15th Conference of the Parties to the UNFCCC” (North American Leaders 2009). An example of explicit reciprocity is the European Union’s Copenhagen Accord pledge to reduce its emissions by 20 % below 1990 levels by 2020, or to reduce its emissions by 30 % below 1990 levels “provided that other developed countries commit themselves to comparable emissions reductions and that developing countries contribute adequately according to their responsibilities and respective capabilities” (Council of the European Union and the European Commission 2010). Whereas circumspection is similarly relevant for all countries (Landis and Bernauer 2012), reciprocity is more relevant for major powers, since their abatement decisions are likely to inspire more reciprocal action by others.

In this paper, we first develop formal definitions of circumspection and reciprocity and, using a simple analytical framework, derive the domestically optimal carbon price in terms of these parameters. We then numerically examine the relationship between circumspection, reciprocity and optimal carbon prices. In addition, we show how this relationship is affected by assumptions about the shape of the climate change damage function and about the response of the carbon cycle to increasing CO₂ concentrations. We conclude with a brief discussion of policy implications.

2 Modeling approach

2.1 Analytical framework

Consider a game with n players. Each player i produces a certain amount of a public good (abatement of greenhouse gas emissions), denoted by A_i , and subsequently experiences the benefits (reduced climate damages) associated with total global abatement $\sum_j A_j$.

The net present value to player i of a certain set of abatement choices \mathbf{A} is given by

$$\Delta U_i(\mathbf{A}) = -Z_i(A_i) + B_i \left(\sum_j A_j \right) + X_i(\mathbf{A}) \quad (1)$$

where Z_i are abatement costs, B_i are the discounted abatement benefits that depend only on total global abatement, and X_i are discounted benefits that depend on the identity of the abater. Z'_i , B'_i , and X'_i are the relevant marginal quantities.

Denote the conjectural variations $\frac{\partial A_j}{\partial A_i} = \alpha_{i,j}$, and denote $\sum_{j \neq i} \alpha_{i,j} = \alpha_i$. “Reciprocity,” formally defined below, will be a linear scaling of the conjectural variations. The total derivative of player i ’s change in net present value with respect to its own abatement is given by

$$\frac{d\Delta U_i(\mathbf{A})}{dA_i} = -Z'_i(A_i) + B'_i \left(\sum_j A_j \right) (1 + \alpha_i) + \sum_j \frac{\partial X_i(\mathbf{A})}{\partial A_j} \alpha_{i,j}, \quad (2)$$

so at player i ’s optimal abatement level A_i^*

$$Z'_i(A_i^*) = B'_i \left(\sum_j A_j \right) (1 + \alpha_i) + \sum_j \frac{\partial X_i(\mathbf{A})}{\partial A_j} \alpha_{i,j}. \quad (3)$$

The left-hand side here is the marginal abatement cost; the right-hand side is the marginal benefit of abatement and, equivalently in this framework, the social cost of carbon.

We can use the X_i terms to implement circumspection. In particular, let

$$\frac{\partial X_i(\mathbf{A})}{\partial A_i} = \sum_{j \neq i} l_{i,j} B'_j \left(\sum_k A_k \right) \quad (4)$$

where $l_{i,j}$ equals the degree of circumspection adopted by player i toward player j . Most typically, $l_{i,j} \in [0, 1]$, though considerations such as equity weighting could lead to $l_{i,j} > 1$. Since the benefits of circumspection for player i refer to the reduced impact on other players caused by its own abatement (and only by its own abatement), let the other partial derivatives of X_i be zero. Then Eq. 3 can be written as

$$Z'_i(A_i^*) = B'_i \left(\sum_j A_j \right) (1 + \alpha_i) + \sum_{j \neq i} l_{i,j} B'_j \left(\sum_k A_k \right). \quad (5)$$

Henceforth, we define a marginal benefit function such that marginal benefits to each player are proportional to global marginal benefits, with b_i being player i ’s share of global marginal benefits; in particular, $B'_i(\sum_j A_j) = b_i \phi(\sum_j A_j)$, where $\sum_i b_i = 1$. Under this definition,

$$Z'_i(A_i^*) = [b_i(1 + \alpha_i) + \sum_{j \neq i} l_{i,j} b_j] \phi \left(\sum_j A_j \right). \quad (6)$$

To express the conjectural variations $\alpha_{i,j}$, we define a linear reciprocity scale $r_{i,j}$ such that, in the absence of circumspection, if $\forall i, j, r_{i,j} = 0$, the Nash equilibrium is obtained, and that, if $\forall i, j, r_{i,j} = 1$, the socially optimal outcome is obtained.

The Nash equilibrium can be found for each player by setting individual marginal costs equal to individual marginal benefits. So, in Nash equilibrium,

$$Z'_i(A_i^n) = b_i \phi \left(\sum_j A_j^n \right). \quad (7)$$

The social optimum can be obtained by setting individual marginal costs equal to marginal social benefits

$$Z'_i(A_i^s) = \phi \left(\sum_j A_j^s \right). \quad (8)$$

Equations 6 and 8 imply that the social optimum can be obtained if and only if

$$b_i(1 + \alpha_i) + \sum_{j \neq i} l_{i,j} b_j = 1 \quad (9)$$

This condition holds in a pure reciprocity, zero circumspection case if

$$\alpha_i = \frac{1 - b_i}{b_i}, \quad (10)$$

a condition that can be satisfied if $\alpha_{i,j} = \frac{b_j}{b_i}$. Accordingly, we define $r_{i,j}$ such that $\alpha_{i,j} = r_{i,j} \frac{b_j}{b_i}$. Equation 9 also holds in a zero reciprocity, pure circumspection case if

$$\sum_{j \neq i} l_{i,j} b_j = 1 - b_i, \quad (11)$$

a condition which can be satisfied if $l_{i,j} = 1$.

Employing the reciprocity scale for α , we can write Eq. 6 as

$$Z'_i(A_i^*) = \left[b_i + \sum_{j \neq i} (r_{i,j} + l_{i,j}) b_j \right] \phi \left(\sum_j A_j \right) \quad (12)$$

This is the central equation of the model.

2.2 Numerical implementation

The nonlinear set of n equations defined by Eq. 12 can be solved numerically for n players. We consider a 14-player case. Reference net present value (NPV) Gross Domestic Product (GDP) and 21st century cumulative emissions are based upon scenario SSP 9 of Eom et al. (2012) (Table S1). SSP 9 is an experimental shared socioeconomic pathway for the 21st century, developed with the Global Change Assessment Model (GCAM). It has moderate population growth (a global population of ~ 9 billion in 2100) and GDP growth (a productivity growth rate of 1.5 %/year in the United States), and it is similar to the “middle-of-the-road” final shared socioeconomic pathway SSP 2 (O'Neill et al. 2012).

2.2.1 Marginal abatement costs

Marginal abatement costs $Z'_i(A_i)$ are assumed to be linear in abatement, derived from total abatement costs $Z_i(A_i)$ that, as a fraction of player GDP, are a quadratic function of percent national emissions abated.

$$\frac{Z_i(A_i)}{Y_i} = \frac{1}{2}z \left(\frac{A_i}{E_i} \right)^2 \quad (13)$$

$$\frac{Z'_i(A_i)}{Y_i} = z \frac{A_i}{E_i^2} \quad (14)$$

where Y_i is the reference (net present value, at a 3 % social discount rate) GDP of player i , and E_i is its reference cumulative emissions. So that socially optimal cumulative abatement levels are similar to those projected by matDICE (Kopp et al. 2012), an integrated assessment model similar to the DICE model of Nordhaus (2008), z is set equal to 0.06.

2.2.2 Marginal benefits of abatement

The share of benefits assigned to any given player is proportional to its share of global NPV GDP, $b_i = Y_i / \sum_j Y_j$. Discount rates are assumed to be constant at 3 % per year. The global marginal benefit function ϕ is either constant ($\phi = \phi_0$) or linearly declining in cumulative total abatement ($\phi = \phi_0 - m \sum_j A_j$), with ϕ_0 and m defined such that global marginal benefits resemble those estimated with matDICE.

In matDICE, as in DICE, total damages as a function of temperature are given by

$$D(T)/Y = 1 - \frac{1}{1 + \alpha T^\beta} \approx \alpha T^\beta \quad (15)$$

where Y is global GDP. We match the constant marginal benefit function in the analytical model with the standard DICE quadratic damage function ($\beta = 2$, $\alpha = 0.28 \text{ \%}/^\circ\text{C}^2$), and the linearly declining marginal benefit function with a cubic damage function ($\beta = 3$, $\alpha = 0.19 \text{ \%}/^\circ\text{C}^3$) (Fig. 1a–c). The two damage functions are calibrated to yield the same damages at 1.5° warming, an anchor point chosen so that the globally optimal trajectory with the cubic damage function keeps temperatures below the Cancun Accord target of 2°C . (Non- CO_2 climate forcers are neglected for this calculation.) In benefit-cost optimization mode, the quadratic damage function leads to optimal peak warming in 2135 at 2.7°C and optimal CO_2 concentration peaking in 2115 at 560 ppm. Using the cubic damage function, optimal warming peaks in 2095 at 2.0°C and optimal CO_2 concentration peaks in 2075 at 477 ppm.

2.2.3 Solution algorithm

With the above parameter choices, the n equations represented by Eq. 12 are fully specified except for the exogenous reciprocity and circumspection parameters. However, if these equations are solved for arbitrary values of $r_{i,j}$ (i.e., if each player is independently optimizing based on their own circumspection and expectations about reciprocity) the solution will not in general be consistent with the specified conjectural variations. Since the game represents a century of abatement choices, this inconsistency is not desirable; presumably, over the century, players will calibrate their expectations about reciprocity against other players' actions.

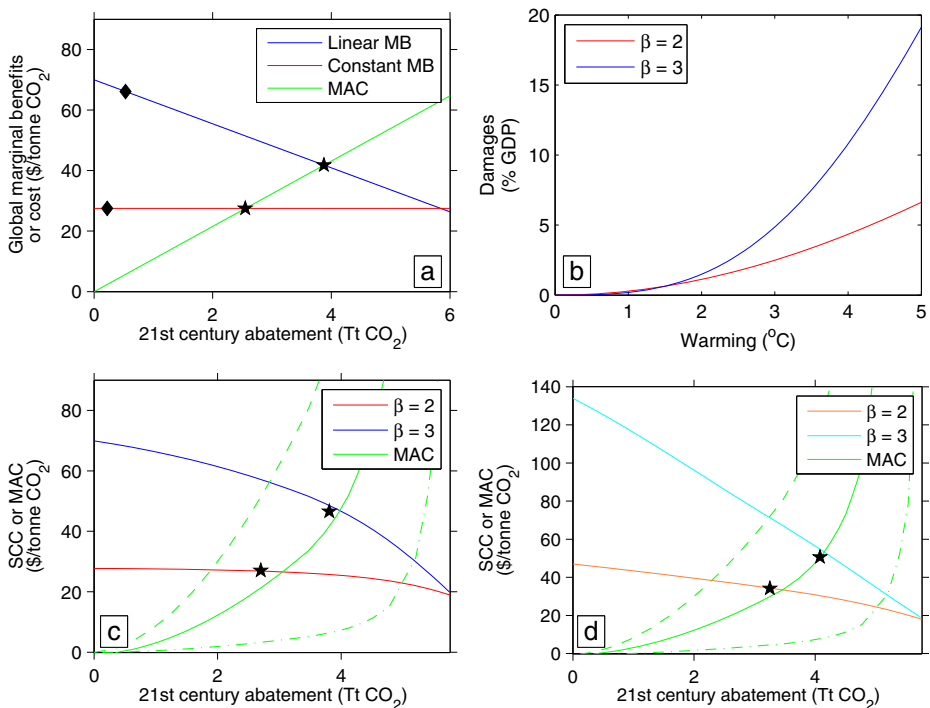


Fig. 1 **a** Two marginal global benefit curves $\phi(A)$ (linearly declining: blue; constant: red) and the global marginal abatement cost curve (green) used to implement the simple analytical model. Stars/diamonds indicate the global abatement level and global marginal benefits at the social optima/Nash equilibria. **b** matDICE damage curves (damages as % of global GDP) with $\beta = 2$ (red) and $\beta = 3$ (blue). **c** Social cost of carbon functions for 2015 at a 3 % discount rate from matDICE for the two damage functions (red, blue) and the global marginal abatement cost curve (MAC) (green) for 2015/2035/2055 (dash-dotted/solid/dashed), under abatement pathways with linearly increasing abatement fractions (see the description of Class B pathways in the [Supplementary Material](#)). Stars indicate the 2015 SCC under globally optimized abatement pathways. **d** As in (c), but with a constant climate response to emissions of 2°C/Tt C. Note change in scale

To avoid this inconsistency, we assume that player 1 is dominant, making its own assumptions about reciprocity and circumspection, and that other players respond to player 1 in a way consistent with player 1's conjectural variations. For simplicity, we also assume that player 1 exhibits equal circumspection toward all other players and that it expects identical reciprocity from all other players. Accordingly, we set $r_{1,j} = r$ and $l_{1,j} = l$ for all $j \neq 1$.

We also set $r_{i,j} + l_{i,j} = r$ for all $i \neq 1, j$. The interpretation of this assumption is that r reflects a belief about the general degree of cooperativeness in the world, and that, among players other than player 1, this cooperativeness could be a result of either reciprocity or circumspection. This closure allows $\alpha_{j,i} = 1/\alpha_{i,j}$ (equivalently, $r_{j,i} = \frac{b_{j,i}^2}{b_{i,j}^2 r_{i,j}}$); in other words, it allows for consistent conjectural variations.

Under these assumptions, $(r, l) = (0, 0)$ leads to the Nash equilibrium and $(r, l) = (1, 0)$ achieves the social optimum. For this analysis, we identify player 1 with the United States.

3 Results and discussion

3.1 Optimal carbon prices

In general, the use of a global SCC in domestic BCA can be motivated by assumptions of full reciprocity, complete circumspection, or an intermediate combination of the two. However, the global SCC may vary with decreasing climate change and thus with increasing global abatement. As a consequence, the global SCC calculated off of a BAU scenario (henceforth, global BAU SCC) may differ from the global SCC calculated off of the globally optimal policy scenario (henceforth, global policy SCC). The use of a global BAU SCC cannot generally be justified based on reciprocity; if there were reciprocity, the world would no longer be following a BAU scenario. Except in the special case where marginal benefits do not vary with abatement (meaning that the global BAU SCC equals the global policy SCC), the choice of the global BAU SCC makes sense only on grounds of complete circumspection.

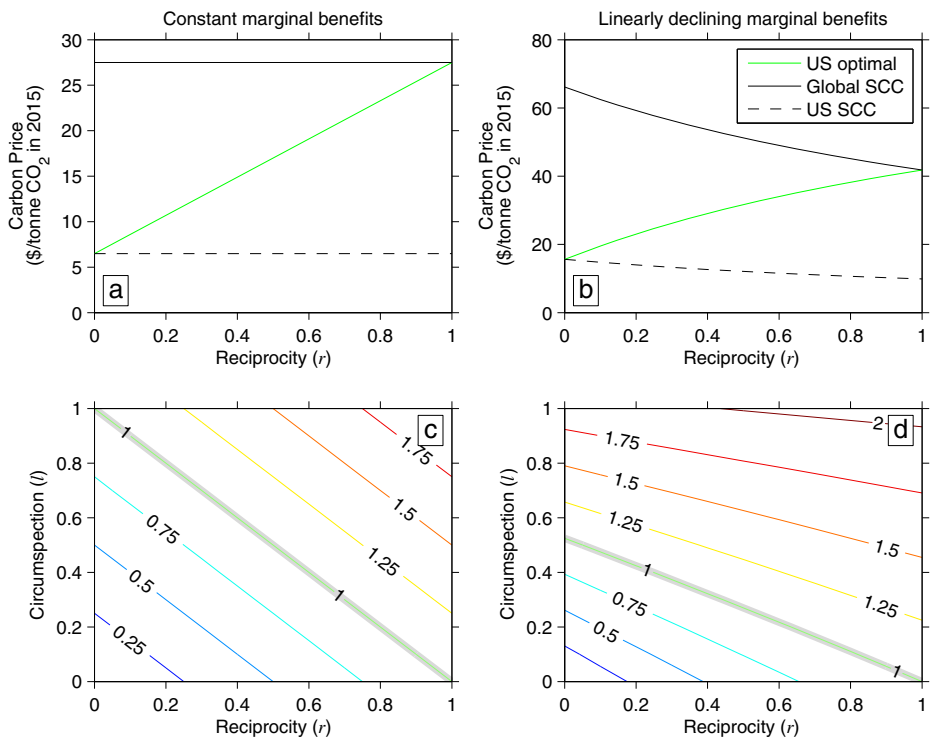


Fig. 2 **a, b** Illustrative U.S. (black dashed) and global (black solid) SCC curves and the optimal U.S. carbon price (green). On the black solid curves, the global BAU SCC occurs at $r = 0$ and the global policy SCC at $r = 1$. **c, d** Fraction of the gap between the domestic SCC without reciprocity or circumspection (i.e., the Nash equilibrium carbon price) and the global policy SCC (the socially optimal carbon price) that is closed under different levels of reciprocity and circumspection. **a, c** shows values for marginal benefits of abatement that are constant in abatement, while **b, d** shows the same for marginal benefits that are linearly declining in abatement

In the absence of circumspection, the domestically optimal carbon price will equal the global policy SCC when full reciprocity is assumed. This can be seen analytically in Eq. 12. If marginal benefits are roughly constant with abatement, the domestically optimal carbon price will approach the single global SCC linearly with increasing reciprocity (Fig. 2a). On the other hand, if marginal benefits decrease with abatement, the domestically optimal carbon price will approach the global policy SCC concavely with increasing reciprocity (Fig. 2b); half the reciprocity needed to achieve the globally optimal level of abatement will close the gap between the domestically optimal price and the global policy SCC by more than half. Intuitively, this can be understood by noting that, with marginal benefits declining in domestic abatement, increasing reciprocity not only raises the domestically optimal price by scaling the benefits of abatement but also decreases global marginal benefits. Analytically, in Eq. 12, $\phi(\sum_j A_j)$ is declining while its multiplier $\sum_{j \neq i} r_{i,j} b_j$ is increasing.

The gap between the global policy SCC and the optimal domestic carbon price reflects the level of circumspection required to justify using the global policy SCC. If ϕ is constant, then, as observed in Fig. 2c, Eq. 12 is linear in reciprocity and circumspection, with reciprocity and circumspection perfectly substitutable for one another. If global marginal benefits are declining in global abatement, however, $\phi(\sum_j A_j)$ will decline more in response to increasing reciprocity than in response to increasing circumspection, as the former directly affects all global emissions, while the latter affects only a single player's emissions. The symmetry between reciprocity and circumspection is accordingly broken; while, in the absence of circumspection, complete reciprocity is still required to close the gap between the global policy SCC and the optimal domestic carbon price, incomplete circumspection can accomplish the same task in the absence of reciprocity. In the example in Fig. 2d, for example, the global policy SCC can be justified with about 50 % circumspection assuming no reciprocity, or with about 25 % circumspection assuming 50 % reciprocity.

3.2 Are marginal benefits decreasing?

Are the marginal benefits of climate change mitigation decreasing with abatement? This question can be considered by decomposing marginal damages with respect to cumulative emissions $\frac{\partial D}{\partial E}$, which are equivalent to the marginal benefits of abatement, into the product of the partial derivatives of damages D with respect to temperature T , temperature with respect to radiative forcing F , forcing with respect to atmospheric CO₂ concentrations C , and atmospheric CO₂ concentrations with respect to cumulative anthropogenic emissions E :

$$\frac{\partial D}{\partial E} = \frac{\partial D}{\partial T} \times \frac{\partial T}{\partial F} \times \frac{\partial F}{\partial C} \times \frac{\partial C}{\partial E}. \quad (16)$$

Temperature is approximately linear in forcing (Hansen et al. 1981), and (neglecting non-CO₂ forcers) forcing is logarithmic in CO₂ concentration (Ramaswamy et al. 2001). DICE and similar integrated assessment models employ estimates of damages (as a fraction of GDP) that are approximate power functions of temperature (e.g., Eq. 15). Assuming CO₂ concentration varies linearly with E —an assumption that

holds in the long-term if, as in most integrated assessment models, climate-carbon cycle feedbacks are neglected (Le Quéré et al. 2009)—we find

$$\frac{\partial D}{\partial E} \propto \frac{T^{\beta-1}}{C} \propto \frac{[\log(C/C_0)]^{\beta-1}}{C} \propto \frac{[\log(1 + fE/C_0)]^{\beta-1}}{1 + fE/C_0}, \quad (17)$$

where β is the exponent of temperature in the damage function, f is the fraction of emissions that accumulate in the atmosphere and C_0 is the pre-industrial concentration of atmospheric CO_2 . If $f \approx 0.5$, then for $\beta = 2$, as in the standard configuration of DICE, this expression has a broad plateau centered around 7,000 Gt CO_2 cumulative emissions, a range close to BAU emissions through the 21st century under many scenarios. Consequently, marginal damages will be roughly constant in cumulative emissions, and marginal benefits will be roughly constant in cumulative abatement.

Some authors, however, regard the quadratic relationship between temperature and damages as conservative, and suggest that a risk-based analysis of climate change should consider the plausibility of higher-order exponents (e.g., Hope 2006; Ackerman et al. 2010; Kopp et al. 2012; Weitzman 2012). Higher-order polynomials give rise to marginal damage curves that plateau at cumulative emissions in excess of BAU and are consequently monotonically increasing in cumulative emissions for all relevant emissions levels (marginal benefit curves that are monotonically decreasing in abatement for all relevant abatement levels).

Even if a quadratic function accurately represents the relationship between climate damages and temperatures, marginal benefits that decline with abatement can arise for another reason: the CO_2 buffering capacity of the ocean declines as the atmospheric and marine inorganic carbon inventory increases (Goodwin et al. 2009). Other climate-carbon cycle feedbacks may also lead the airborne fraction of emissions to increase (Matthews et al. 2009; Le Quéré et al. 2009). Depending on the strength of these feedbacks, temperature may be better approximated as a linear rather than a logarithmic function of cumulative emissions (Matthews et al. 2009; Goodwin et al. 2009). In this case

$$\frac{\partial D}{\partial E} \propto T^{\beta-1} \propto E^{\beta-1}, \quad (18)$$

which is increasing in emissions and yields marginal benefits that decline in abatement for any $\beta > 1$.

To compare the relationships in Eqs. 17 and 18 with those generated by a numerical model that incorporates temporal dynamics, we used matDICE to calculate the SCC as a function of cumulative emissions for two different damage functions with different values of β (Fig. 1b) and two different relationships between emissions and temperature—either the standard DICE climate and carbon cycle model (Fig. 1c), or a constant climate response to emissions of $2^\circ\text{C}/\text{Tt}$ cumulative C emissions ($0.55^\circ\text{C}/\text{Tt}$ CO_2) (Fig. 1d). The results are reasonably consistent with the analytical expressions, though the best-fit effective values of β differ somewhat from the value of β that appears in the damage function. This is a result of the temporal distribution of damages; alternative pathways to the same cumulative emissions give rise to SCC curves with similar end points but exhibiting different degrees of curvature (see [Supplementary Material](#)).

3.3 A comment on discounting and uncertainty

This analysis is focused on conceptual relationships, not numerical values. We employ deterministic climate and economic projections and a constant 3 % social discount rate, but alternative assumptions about uncertainty, time discounting, risk aversion and equity weighting should not qualitatively affect the conceptual conclusions. Equations 16–18 provide insight into how changes in these parameters would affect results. Incorporating risk aversion in combination with increased uncertainty (e.g., Kopp et al. 2012; Anthoff et al. 2009) places greater weight on bad states of the world and effectively increases β . Increasing time discounting reduces the period of concern and the temperature of concern, effectively reducing T . It also reduces the NPV GDP, and therefore the constant of proportionality in the marginal damage expressions. The effect of equity weights (e.g., Anthoff and Tol 2010) is ambiguous and will depend upon other factors such as risk aversion.

4 Policy implications

At present, the U.S. government employs a global SCC for domestic regulatory analyses. More specifically, it employs SCC estimates based predominantly on scenarios in which there is no significant global mitigation. Four of the five scenarios assume no global mitigation, the fifth assumes a 550 ppm CO₂ stabilization scenario, and all five are considered equally probable (Interagency Working Group on the Social Cost of Carbon 2010). The four BAU scenarios imply zero reciprocity—otherwise, the world would move from BAU to some higher abatement state—while the fifth suggests but does not require non-zero reciprocity. The use of a global BAU SCC can be motivated on grounds of reciprocity only when marginal benefits are approximately constant in abatement; otherwise it implies a considerable degree of circumspection. In contrast, the use of the global policy SCC could be supported on grounds of either reciprocity or circumspection.

If the marginal benefits of abatement are constant, then circumspection and reciprocity are perfect substitutes, so that either full circumspection, full reciprocity, or a linear mixture can support the use of the single global SCC. If marginal benefits are declining, however, increasing reciprocity leads the optimal domestic carbon price to approach the global policy SCC concavely, meaning that even imperfect reciprocity can come close to supporting the global policy SCC. Moreover, in the declining marginal benefits case, partial circumspection can support the use of the global policy SCC without reciprocity, and even less circumspection is needed when some reciprocity is assumed. The possibility of greater-than-quadratic climate damages and the expectation of weakening carbon sinks can both give rise to declining marginal damages, as shown both analytically and numerically.

While motivated by the desire to refine SCC estimates used in regulatory analysis, the circumspection/reciprocity framework highlights choices any government—national, sub-national, or supra-national—must make when utilizing a carbon price. Aside from the central physical and economic projections that go into constructing SCC estimates, the optimal carbon price trajectory also depends critically on judgments regarding circumspection and reciprocity. The implications of these judgments depend upon the nature of both climate damages and the global carbon cycle.

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Supplementary Material

S.1 Path-dependency of the social cost of carbon

Although the transient climate response to carbon dioxide emissions can be assessed based on cumulative emissions (Matthews et al, 2009), and on a multi-decadal timescale is nearly independent of emissions pathway, the same is not necessarily true of discounted damages. If two emissions pathways have equivalent cumulative emissions, but in one abatement is delayed relative to the other, near-term temperatures and thus discounted damages will be greater in the pathway with delayed abatement.

To evaluate the extent of the discrepancy introduced when we collapse climate decision-making to a single time period, as in the analytical model described in this paper, we use the matDICE model with the MiniCAM-based reference scenario of Kopp et al (2012) to assess the 2015 and 2055 social cost of carbon as a function of cumulative carbon emissions to 2100 (Figs. S-1, S-2). (In this analysis, valuations are in constant 2005 USD.) The reference scenario has cumulative emissions to 2100 of 7,780 Gt CO₂, of which 1,600 Gt CO₂ are emitted before the year 2000 (Boden et al, 2010; Houghton, 2008). Non-CO₂ forcers are ignored for these calculations, and climate sensitivity is kept at its most likely value of 3°C per CO₂ doubling (Randall et al, 2007). Note that neither DICE nor matDICE include climate-carbon cycle feedbacks or changes in the buffering capacity of the ocean at increased CO₂ concentrations; as a consequence, the decline in both atmospheric CO₂ and temperature after emissions cease is more rapid than in higher complexity models (van Vuuren et al, 2011). The warming is more concave in cumulative emissions than it is in more detailed models, which are more nearly linear (Figure S-1d) (Matthews et al, 2009).

We calculate emissions and temperature pathways (Figure S-1) and social cost of carbon estimates at a constant 3% discount rate (Figure S-2a,b) for two different classes of emissions pathways. Class B has a fraction of business-as-usual (BAU) emissions abated that ramps up linearly over the course of the twenty-first century; the less realistic class A abates a fraction of BAU emissions that is constant over the course of the century. All pathways assume emissions go to zero in 2100. Comparing members of the two classes with similar cumulative emission levels indicates that the path-dependency of the temperature response is minimal and that of the SCC is fairly small.

To assess the impact of neglecting climate-carbon cycle feedbacks, we also consider the same classes of emissions pathways under a climate in which global mean temperature is proportional to cumulative emissions (Figs. S-1e,f, S-2c,d). As expected from equation 18, the SCC curves in this case do not exhibit the plateaus seen in S-2a,b but are instead monotonically increasing for both quadratic and cubic damage functions.

Least squares fits of equations 17 and 18 to the curves are shown in Figure S-2. The equations are fit in the form

$$\frac{\partial D}{\partial E} = \hat{A} \frac{[\log(1 + \hat{f}(E + \widehat{\Delta E})/C_0)]^{\hat{\beta}-1}}{1 + \hat{f}(E + \widehat{\Delta E})/C_0} \quad (\text{S-1})$$

$$\frac{\partial D}{\partial E} = \hat{A}(E + \widehat{\Delta E})^{\hat{\beta}-1} \quad (\text{S-2})$$

Fit parameters are shown in Table S-2, along with the mean residual sum of squares. \hat{A} is a scale factor, $\hat{\beta}_{\text{eff}}$ is the effective β value and \hat{f} , which is constrained to be between

0.3 and 0.7, is the effective airborne fraction. $\widehat{\Delta E}$ is an offset to cumulative emissions that optimizes the fit; it appears in the figures as the negative of the x-intercept of the best-fit curve.

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Table S-1 Parameters for the analytical model

	USA	AFR	AUNZ	CA	CHN	EEU	FSU	IND	JPN	KOR	LAM	ME	SEA	WEU	Total
NPV GDP (10^{12} USD) (Y)	625	121	34	46	393	36	41	219	180	33	192	80	179	470	2,025
BAU Emissions (Gt CO ₂) (E)	598	748	55	70	1,511	106	290	781	106	55	323	293	557	510	6,002
b_i	0.24	0.05	0.01	0.02	0.15	0.01	0.02	0.08	0.07	0.01	0.07	0.03	0.07	0.18	1.00
z	0.06														
ϕ_0 (const. case)	\$28/tonne CO ₂														
ϕ_0 (linear case)	\$70/tonne CO ₂														
m	\$7.3/tonne CO ₂ /Tt CO ₂														

Regions: USA – United States; AFR – Africa; AUNZ – Australia and New Zealand; CA – Canada; CHN – China; EEU – Eastern Europe; FSU – Former Soviet Union; IND – India; JPN – Japan; KOR – Korea; LAM – Latin America; ME – Middle East; SEA – Southeast Asia; WEU – Western Europe.

Table S-2 Least squares fits to matDICE SCC curves

	2015 SCC					2055 SCC				
	\hat{A}	$\widehat{\Delta E}$ (Gt CO ₂)	$\hat{\beta}_{\text{eff}}$	\hat{f}	\overline{RSS}	\hat{A}	$\widehat{\Delta E}$ (Gt CO ₂)	$\hat{\beta}_{\text{eff}}$	\hat{f}	\overline{RSS}
$\beta = 2$, matDICE climate										
class A	75	-60	1.9	0.38	0.0003	157	-630	2.1	0.70	0.01
class B	74	-200	2.2	0.70	0.02	140	-1230	1.6	0.32	0.007
$\beta = 3$, matDICE climate										
class A	166	-120	3.0	0.62	0.05	410	-840	2.9	0.70	0.6
class B	205	-1190	2.0	0.30	0.06	430	-1130	2.6	0.70	0.2
$\beta = 2$, 2°C/Tt C										
class A	26	260	1.8		0.005	68	-350	1.8		0.06
class B	36	-1230	1.4		0.01	82	-1070	1.6		0.09
$\beta = 3$, 2°C/Tt C										
class A	55	-460	2.3		0.8	173	-960	2.3		7
class B	80	-1270	1.9		0.08	213	-1370	2.1		4

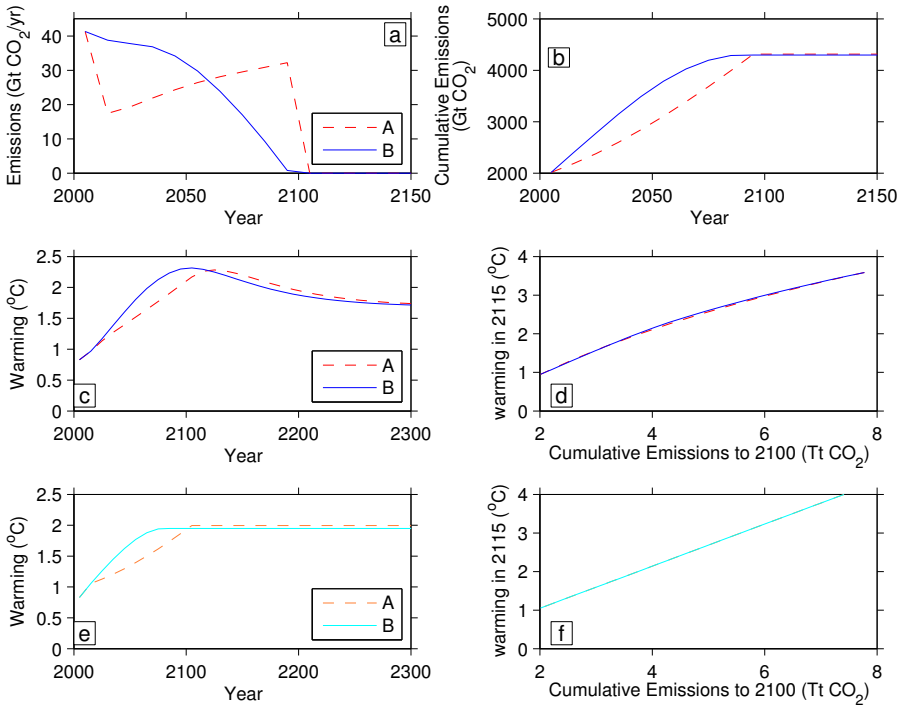


Fig. S-1 (a) Two different emissions pathways in matDICE yielding similar cumulative emissions levels. (b,c) Corresponding cumulative emissions and temperature trajectories. (d) Warming in 2115 as a function of cumulative emissions to 2100 for class A (red) and class B (blue) trajectories. (e,f) as (c,d) but with a constant climate response to emissions of 2°C/Tt C.

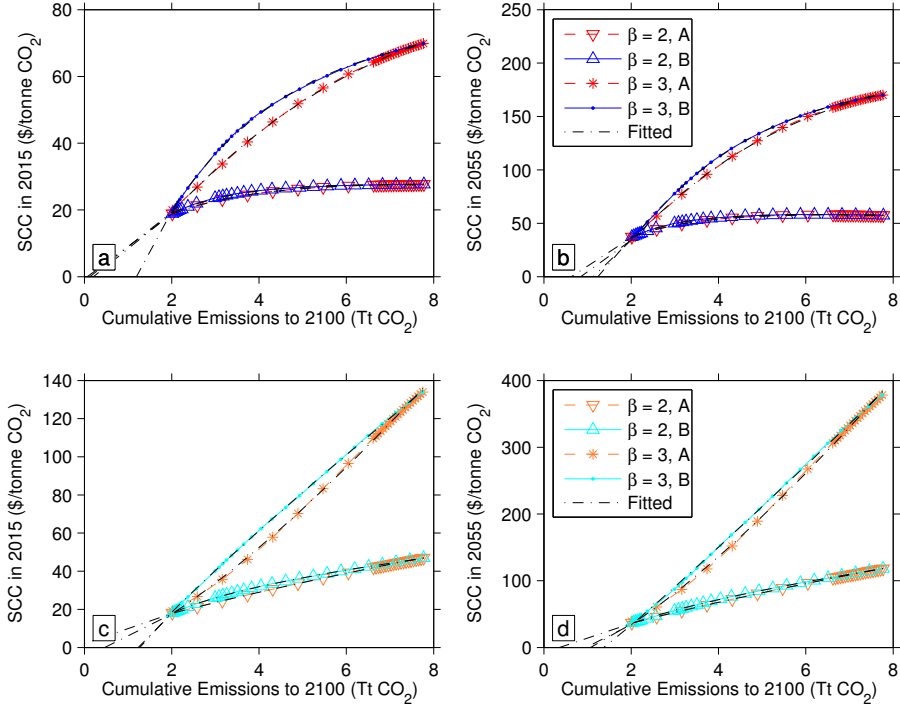


Fig. S-2 (a) Social cost of carbon in 2015 at a 3% discount rate from matDICE for quadratic (triangles) and cubic (dots and stars) damage functions, and fits of equation 17. (b) Social cost of carbon in 2055. (c,d) as (a,b) but with a constant climate response to emissions of 2°C/Tt C, and fits of equation 18. Note differences in scale between panels.