Which Social Cost of Carbon? A Theoretical Perspective

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Abstract: This paper develops a theoretical foundation for the social cost of carbon (SCC). The model highlights the source of debate over whether countries should use the global or domestic SCC for regulatory impact analysis. I identify conditions under which a country's decision to internalize the global SCC is individually rational. I show that obtaining international consensus on a uniform value to internalize will be more challenging than often appreciated. I introduce the notion of a "preferred SCC" to reflect each country's preference conditional on a true value of the global SCC and a distribution of the domestic SCCs among countries. While all countries have a preferred SCC greater than their domestic SCC, a country's preferred SCC can be greater than or less than the global SCC. How these preferences translate into agreement depends on institutional arrangements for collective decision making, for which I provide empirical evidence based on various decision rules.

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THE PROBLEM OF CLIMATE CHANGE is the problem of a global externality. The social cost of carbon (SCC) is a concept that reflects the marginal external costs of emissions: it represents the monetized damage caused by each additional unit of carbon dioxide, or the carbon equivalent of another greenhouse gas, emitted into the atmosphere. Many countries have begun accounting for the SCC in regulatory impact analyses of domestic policies.[1] The starting point for the present paper is recognizing

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1. The countries are Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Israel, Netherlands, New Zealand, Norway, Sweden, United Kingdom, the United States, and the Eu-

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that these countries are taking into account an estimate of the global benefits of reducing CO_2 emissions (i.e., avoided damages worldwide) when comparing the costs and benefits of domestic regulations. Between 2010 and 2016, for example, the United States used a central estimate of \$40 per metric ton of CO_2 emitted in 2015 (in 2014\$), with increasing numbers for each year thereafter (Interagency Working Group 2013).

There is, however, growing debate about whether the global SCC is appropriate for benefit-cost analysis of domestic policy. The practice has been justified on the basis that climate change is a unique problem because of its scale as a global externality; that application of the global SCC among all countries would lead to globally efficient emissions; and that climate policy takes place in the context of international relations where one country's actions are used to leverage those of others, and no one country can solve the problem of climate change alone (Interagency Working Group 2010; Greenstone et al. 2013; Pizer et al. 2014).

The other side of the debate emphasizes that using global benefits is a departure from the conventional practice of regulatory impact analysis, especially in the United States, where benefit-cost analysis has focused traditionally on comparing domestic benefits and costs (Dudley and Mannix 2014; Darmstadter 2016; Fraas et al. 2016; Gayer and Viscusi 2016).[2] The critics argue that unilateral policy for any one country should account for only the domestic share of the SCC and that broadening the scope to include global benefits has potentially far-reaching implications for the allocation of societal resources. Questions also arise about consistency with individual rationality (i.e., self-interest) from any one country's perspective. In the United States, these arguments were the basis for President Trump's almost immediate rollback of the Obama administration's use of the SCC for evaluating domestic policy (Executive Order 13783, 2017).

Despite the widespread use of the SCC for evaluating climate-related policies, and the growing debate about its appropriate scope, there is surprisingly little research on the theoretical basis of the SCC and how it should be used for policy analysis. The existing literature focuses almost exclusively on producing empirical estimates and refining the underlying methods employed in integrated assessment models (IAMs). This paper, in contrast, develops a theoretical foundation for the SCC to highlight points of disagreement in the debate over whether countries should use the global or domestic SCC. Moreover, I identify conditions under which a country's decision to internalize the global SCC is individually rational, yet I also show how obtaining international consensus on a particular value of the global SCC will be more challenging than often appreciated.

ropean Union Commission. See Smith and Braathen (2015) for a survey on the use of the SCC among OECD countries.

2. For a legal perspective, see Rowell (2015) for a detailed discussion about the precedence and potential challenges that arise from using the global SCC for regulatory impact analysis in the United States.

The next section begins with the basic setup of a static model where each country chooses its emissions policy, recognizing that aggregate emissions generate a global public "bad." The setup makes immediately clear the distinction between global and domestic definitions of the SCC. Analysis in section 2 shows how internalizing the global SCC is consistent with efficiency of global emissions, and internalizing the domestic SCC is consistent with a Nash equilibrium among countries on their choice of emissions. I then use the model in section 3 to show potential distributional effects of moving from equilibrium to efficient emissions, along with suggestive empirical evidence based on the regional calibration in the C-DICE model (Nordhaus 2015).

Section 4 moves directly to questions about individual rationality and a country's choice of internalizing the global or domestic SCC. I extend the basic model in two ways to account for the real-world institutional context where climate policy and international negotiations take place. First, building on the international relations argument for leadership and leverage, I replace the assumption of Nash behavior with conjectures about how other countries will respond to one's own choice of emissions. Second, taking account of the dynamic way that countries will make emissions decisions over time, I extend the static setup of the model to a repeated game and consider basic folk theorem results. Both modeling approaches show that a country's choice to internalize the global SCC can be individually rational. The results provide what is to the best of my knowledge the first formally derived microeconomic justification for countries to internalize the global SCC, and the necessary conditions are informative for policy design.

But on what value of the global SCC should we expect countries to agree? From an economics perspective, and setting aside assumptions about the discount rate, the SCC is generally perceived as an objective parameter, the estimates of which are limited primarily by empirical methods and data availability. For political purposes, however, seeking the one right estimate of the global SCC fails to recognize the heterogeneous incentives on the part of sovereign countries. In section 5, I introduce the notion of a "preferred SCC" (PSCC) to reflect each country's preference for a globally internalized shadow value on emissions, conditional on a true value of the global SCC and a distribution of the domestic SCCs among countries. While all countries have a PSCC greater than their domestic SCC, a country's PSCC can be greater than or less than the global SCC. How these preferences translate into agreement therefore depends on institutional arrangements for collective decision making, for which I provide some empirical evidence based again on the C-DICE model and various decision rules.

In the final section, I conclude the paper with a summary of the main results and policy implications. A central finding is that internalizing the global SCC when setting domestic policy or conducting regulatory impact analysis can be in a country's own self-interest. There is, however, a need for more research on the theoretical basis of the SCC and its use for policy analysis. The analysis here demonstrates how establishing and using the global SCC among sovereign nations is not simply an application of estimating and internalizing an externality.

1. THE MODEL SETUP

I construct the simplest model possible to illustrate the key ideas. Countries are indexed $i = 1, \dots, n$ with $n \geq 2$. Each country has emissions x_i, and the initial version of the model is static.[3] The aggregate level of emissions, $X = \Sigma_{i=1}^{n} x_i = x_i + X_{-i}$, is a global public "bad." This means that emissions anywhere on the planet affect all countries, and I assume the impact on each country is negative. The damages of emissions in country i are $D_i(X) = \alpha_i X$, where $\alpha_i > 0$, and the linearity assumption is made for simplicity. The benefits of emissions in country i are $B_i(x_i)$, where $B_i'(x_i) > 0$ and $B_i''(x_i) < 0$. I have assumed here, again for simplicity, that both the benefits and damages are measured in equivalent monetary units.

A few observations are useful about the country-level specification of the damage and benefit functions. The damage function for each country can be written as consisting of two terms, $D_i(X) = \alpha_i X_{-i} + \alpha_i x_i$. The first term reflects the damage in country i from emissions in all other countries. The second term reflects the damage in country i from its own emissions. While the damages with a domestic origin are internal to the country, they are external to individual agents within the country. Internalizing domestic damages from domestic emissions therefore requires some form of government intervention. The interventions can be either quantity or price based. A quantity-based policy would set x_i in ways consistent with, for example, direct regulation or a cap-and-trade program. A price-based policy would set a per unit price p_i on emissions (e.g., a carbon tax) that would determine a country's emissions according to $x_i(p_i) = \{x_i : B_i'(x_i) = p_i\}$, which represents each country's demand for emissions.

The simple setup of this model makes immediately clear the differences between two notions of the SCC:

Definition 1 (DSCC): The domestic social cost of carbon is α_i for all i.

Definition 2 (GSCC): The global social cost of carbon is $A = \Sigma_{i=1}^{n} \alpha_i$.

Both the DSCC and the GSCC provide a measure of monetized, marginal damages from emissions but differ in their political and therefore geographic scope. The DSCC measures the marginal damages to each country individually, whereas the GSCC measures the global marginal damages, which are the sum of the DSCCs across all countries.

Most of the empirical evidence on the GSCC comes from IAMs. Although IAMs are not without critics (Pindyck 2013, 2017), they provide the leading approach among researchers and policy makers for estimating the GSCC (Metcalf and Stock 2017). As the IAMs have become more detailed over time, greater efforts have been made to in-

3. The one-period version of the model can be interpreted as a single long period or extended to reflect a repeated game with a constant payoff structure, as in section 4.2.

crease the spatial resolution of costs and benefits. Specifically, several models calculate estimates of the DSCC for different countries or, in most cases, regions. Nordhaus (2014) summarizes the regional SCC estimates for different models and observes that while there is little consensus on the partitioning of the GSCC by region, no one region or country appears to dominate the total. In a subsequent paper, Nordhaus (2015) merges the results to derive a regional decomposition of the GSCC based on an average of three models.[4]

In figure 1, I report the decomposition to provide a sense of the empirical heterogeneity in the DSCC, recognizing that some estimates are for regions rather than countries. It is important to note that these are the assumed damages across several models, rather than empirical estimates. Across the distribution, Nordhaus (2015) observes that the DSCCs are roughly proportional to discounted gross domestic products (GDPs), with deviations based on the modelers' assessments of geographic differences in climate sensitivity. Based on the vertical axis on the left-hand side, the estimates range from nearly 14% of the GSCC for the European Union to less than 1% for South Africa. The figure also illustrates how the percentage distribution partitions a GSCC of $40 among different countries or regions.[5] For example, given a GSCC of $40 per ton, the US percentage share translates into a DSCC of $4.24.

2. EFFICIENCY VERSUS EQUILIBRIUM

I now consider how the different measures of the social cost of carbon—the GSCC and the DSCCs—relate to globally efficient and equilibrium levels of emissions policy. The primary contribution of this section is to show how the standard approach for studying public goods relates to different notions of the SCC. I begin with global efficiency and the GSCC, before turning to equilibrium policies and the DSCCs. To simultaneously account for quantity- or price-based policies, I consider the shadow value on emissions, denoted s_i, that each country internalizes. The choice of s_i maps into a quantity-based instrument according to the demand function for emissions $x_i(s_i)$ and directly into a price-based instrument with $s_i = p_i$.

When it comes to setting global emissions, the assumed objective is to maximize aggregate surplus. Efficiency therefore requires coordination of the internalized, shadow value on emissions among all countries to solve

$$\max_{s_1,\ldots,s_n} \sum_{i=1}^{n} B_i(x_i(s_i)) - A\sum_{i=1}^{n} x_i(s_i)). \qquad (1)$$

4. See table B-2 in the online appendix to Nordhaus (2015).

5. The estimated percentage decomposition of the GSCC into countries and regions is based on a GSCC of around $20 (Nordhaus 2015). The percentages reported in figure 1 assume that the same percentages hold for a GSCC of $40.

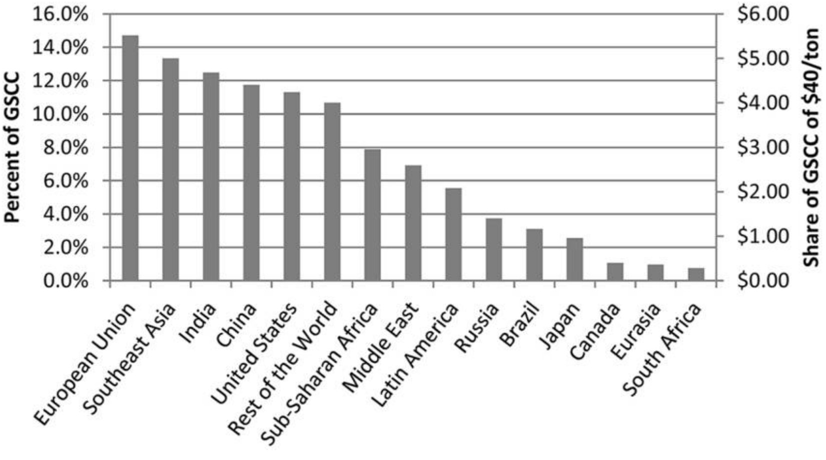

Figure 1. Heterogeneity in the decomposition of the GSCC into the DSCCs across countries or regions based on averaging across three IAMs.

Assuming an interior solution (here and throughout), the conditions that define the solution can be combined as

$$B_1'(x_1(s_1^*)) = \ldots = B_n'(x_i(s_i^*)) = A. \tag{2}$$

The result is intuitive: the marginal benefit of emissions is equated across all countries and equal to the sum of the marginal damages of emissions.[6]

Using each country's demand function for emissions, it is straightforward to see the further implication that satisfying (2) requires $s_i^* = A$ for all i. That is, all countries must internalize the GSCC, which then defines a unique level of Pareto optimal emissions for each country $x_i^* = x_i(s_i^*)$ and thus aggregate emissions, $X^* = \Sigma_{i=1}^n x_i^*$. This, of course, is the efficiency argument in support of all countries internalizing the GSCC for domestic policy.

I now turn to the problem that each country faces based on its own self-interest. While Pareto optimal emissions maximize aggregate surplus, individual countries are focused on maximizing their own net benefits. I begin with the Nash assumption whereby each country takes the emissions policy of others as given. Each country's problem can be written as

6. This is equivalent to stating that the (monetary) marginal costs of abatement are equated across countries, which follows because each country's utility is measured by its monetary payoff. Without this assumption, an analogous condition would require equating the marginal costs of abatement in terms of utility (see Chichilnisky and Heal 1994).

$$\max_{s_i} B_i(x_i(s_i)) - \alpha_i[x_i(s_i) + X_{-i}]. \tag{3}$$

The important feature of this objective function is that each country accounts for its DSCC from global emissions rather than the GSCC. The unique solution will solve

$$B_i'(x_i(\hat{s}_i)) = \alpha_i \text{ for all } i. \tag{4}$$

In this case, each country's demand for emissions implies that $\hat{s}_i = \alpha_i$ for all i.[7] That is, each country chooses to internalize its DSCC, implying domestic emissions levels $\hat{x}_i = x_i(\hat{s}_i)$ for all i and global emissions $\hat{X} = \Sigma_{i=1}^{n}\hat{x}_i$.

It is straightforward to see that equilibrium emissions are inefficiently high in all countries. This follows immediately from the facts that $s_i^* = A > \alpha_i = \hat{s}_i$ and $x_i'(s_i) < 0$ for all i. The result also follows intuitively because emissions provide a global public bad, the marginal damages of which no one country has the incentive to fully internalize with the setup in (3). In other words, every country has an incentive to free ride rather than internalize more than its own costs.

3. DISTRIBUTIONAL CONSIDERATIONS

The previous section established how the globally efficient level of emissions in each country is not an equilibrium. It is important to recognize, however, that all countries would not necessarily prefer the efficient level of emissions, even if it could be sustained. That is, if all countries move from their equilibrium to an efficient level of emissions, there can be winners and losers. In this section, I consider the potential distributional effects upon moving from equilibrium to efficient emissions. To begin, define the respective net benefits for each country as $\hat{v}_i = B_i(\hat{x}_i) - \alpha_i\hat{X}$ and $v_i^* = B_i(x_i^*) - \alpha_i X^*$. Hence the task is to consider different circumstances under which it is possible for $v_i^* - \hat{v}_i \gtreqless 0$.

The simplest and most intuitive case to start with is that of all identical countries, because the efficient level of emissions will always Pareto dominate the equilibrium. By symmetry, each country will have the same level of equilibrium emissions and the same level of Pareto optimal emissions. We can therefore dispense with subscripts for the time being to show that

$$v^* - \hat{v} = [B(x^*) - \alpha n x^*] - [B(\hat{x}) - \alpha n \hat{x}] \tag{5}$$

$$= \alpha n(\hat{x} - x^*) - \int_{x^*}^{\hat{x}} B'(z)dz > 0, \tag{6}$$

7. Note that each country's choice of $\hat{s}_i$ and therefore $\hat{x}_i$ depends on α_i but not X_{-i}. This is an important implication of the assumed linearity of damage functions. While the assumption simplifies the analysis greatly, it should be recognized that, more generally, each country's choice would be a best-response function that depends on the emissions of other countries.

where the inequality follows because $\hat{x} > x^*$, $\alpha n = B'(x^*)$ by (2), and $B''(x) < 0$. In other words, for each country, the avoided damages of lower global emissions (the first term) more than offset the forgone benefits of further reducing its own emissions (the second term). Indeed, the result is quite intuitive upon recognizing that maximizing the sum of net benefits among identical countries is equivalent to maximizing the net benefit for each individual country.

There is, however, no such general result with heterogeneous countries. The more general formulation of (5) and (6) for all i is

$$v_i^* - \hat{v}_i = \alpha_i\left(\hat{X} - X^*\right) - \int_{x_i^*}^{\hat{x}_i} B_i'(z)dz \tag{7}$$

$$= \underbrace{\alpha_i\left(\hat{X}_{-i} - X_{-i}^*\right)}_{>0} + \underbrace{\alpha_i(\hat{x}_i - x_i^*) - \int_{x_i^*}^{\hat{x}_i} B_i'(z)dz}_{<0}, \tag{8}$$

where the signs of the different parts of the expression follow because $\hat{x}_i > x_i^*$ for all countries, $B_i'(\hat{x}_i) = \alpha_i$ by (4), and $B_i''(x_i) < 0$. The important observation is that the overall sign of (8) can be either positive or negative.

Notwithstanding the indeterminate sign, the terms in (8) are useful for building intuition about when a country could be made worse-off or better-off upon moving to the globally efficient level of emissions, without transfers. The first braced part of (8), which is positive, represents the "spillin" benefits that a country receives from the emission reductions in other countries. The term is bigger when country i experiences a greater DSCC and other countries reduce their emissions more. The second braced part of (8) is the net private cost to country i. The first term is the benefit of reducing its own emissions, and the second term is the forgone benefit from reducing emissions. The net effect is always negative, and the magnitude is increasing when the marginal benefits of emissions are greater and when the size of the externality being internalized, A_{-i}, is greater. The latter result follows because $x_i^* \to \hat{x}_i$ as $A_{-i} \to 0$.

The more general concept underlying these different possibilities, which mirrors that for public goods in general, is that moving to a Pareto optimal allocation need not imply a Pareto improvement. It does, however, imply that a Pareto improvement is possible with transfers. We know that $\Sigma_{i=1}^n v_i^* > \Sigma_{i=1}^n \hat{v}_i$ even if it does not hold that $v_i^* > \hat{v}_i$ for all i. It is therefore possible for redistribution of the surplus such that all countries are at least as well off as they were in the initial equilibrium. Indeed, the differences $v_i^* - \hat{v}_i$ for all i can provide a foundation for thinking about climate finance as transfers in an international setting. In particular, we know there exists a set of transfers $(\tau_1, \ldots, \tau_n)$ such that $\Sigma_{i=1}^n \tau_i = 0$ and $v_i^* - \hat{v}_i + \tau_i \geq 0$ for all i, holding strictly for at least one i.

In order to provide some simulation-based empirical evidence, I employ the basic setup in Nordhaus (2015) for the C-DICE model, although I exclude the model's club feature. The model includes the 15 countries (or regions) listed in figure 1 and the respective DSCCs corresponding with a GSCC of $40. The country benefits of emissions are based on the functional form and parameterization in Nordhaus (2015, table B-4).[8] With this setup, I solve for the equilibrium and efficient emissions for each country and report the results of interest in figure 2. Panel A shows each country's abatement of moving from equilibrium to efficient emissions, that is, $\hat{x}_i - x_i^*$. Overall emissions decline by 22%, and the figure shows the percentage of the total reduction attributable to each country. For example, 26% of the reduction comes from China and 9% from the European Union.

Panel B shows the change in welfare $v_i^* - \hat{v}_i$ measured in billions of dollars. While India gains the most, South Africa, Eurasia, and China are all made worse-off without transfers. More generally, the countries/regions made better-off tend to be those with a relatively high DSCC (see fig. 1), meaning that they benefit more from each ton of emission reductions in other countries. Yet pushing in the other direction to make countries worse-off, as shown in equation (8), is having to reduce emissions more and having high marginal benefits of emissions. This explains the case of China, which is calibrated to have the highest (forgone) marginal benefit of emissions (equal to Eurasia). Finally, as must be the case when looking across all countries/regions, the aggregate net benefits clearly exceed the costs.

4. RATIONALIZING THE GSCC

Can it ever be individually rational for a country to internalize more than its DSCC, perhaps even the GSCC? With the model considered thus far, the question is equivalent to asking whether cooperation in a prisoner's dilemma can be individually rational. The answer, of course, is "no," without modification to the model's setup. In this section, I show how basic changes to the setup that reflect the real-world institutional context where climate policy and international negotiations take place can produce a different result. My aim is to illustrate simple possibilities that can spur further theoretical research on this increasingly important, policy-relevant question.

4.1. Conjectural Variations

We have heretofore assumed Nash behavior among countries—that is, each country assumes that its choice of s_i and therefore x_i will have no effect on the emissions of other countries. But this assumption ignores the potential importance of international relations where some countries may reduce their emissions to leverage reductions from other

8. The benefits of emissions are given by $B_i(x_i) = q_i - \lambda_i \mu_i^2 q_i$, where q_i is GDP in 2011 and $\mu_i = (\bar{x}_i - x_i)/\bar{x}_i$ is the emissions intensity relative to 2011 levels denoted by $\bar{x}_i$. The parameter λ_i is the abatement cost parameter that comes from McKinsey (2009) and averaged for the 2020 and 2030 estimates. It is straightforward to verify that the benefits function satisfies the required properties for all $x_i \leq \bar{x}_i$.

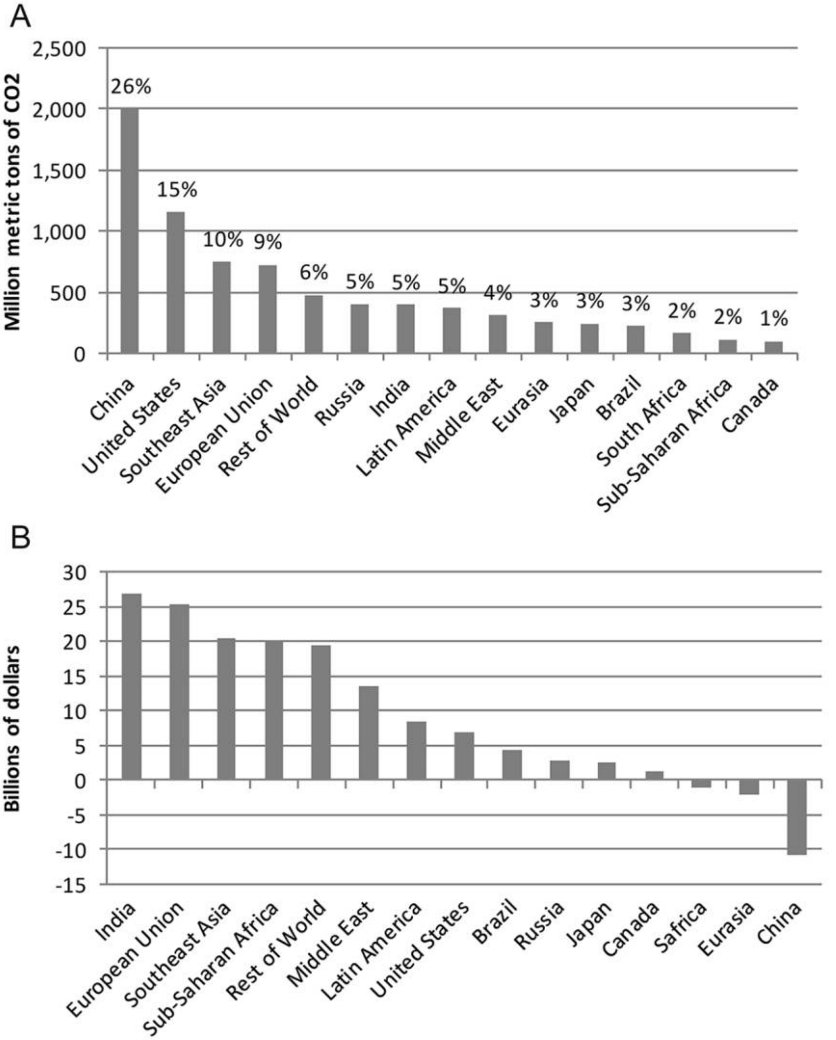

Figure 2. Simulated abatement of countries or regions (*panel A*) and change in welfare (*panel B*) of moving from equilibrium to Pareto optimal emissions without transfers.

countries. One way to account for this relationship is to employ a conjectural variations approach.

Assume that country i has a conjecture about how other countries will change their level of emissions given a change in its own emissions.[9] Here I consider the choices of x_i

9. Kopp and Mignone (2013) employ a similar argument to study how reciprocity interacts with altruistic incentives and the shape of the marginal damage function to affect optimal climate

directly (rather than s_i) in order to simplify notation. The simplest way to characterize a conjecture is with a linear relationship between country i's chosen level of emissions and its expectation about the emissions of others, denoted $\tilde{X}_{-i}$. Specifically, we can write $d\tilde{X}_{-i}/dx_i = \gamma_i > 0$ to capture the way that a country believes a decrease in its own emissions will decrease the emissions of other countries.[10] Note that Nash behavior is consistent with $\gamma_i = 0$ for all i. It follows that $\tilde{X}_{-i} = \gamma_i x_i + \kappa_i$, where κ_i is some constant of integration.

Each country i then solves

$$\max_{x_i} B_i(x_i) - \alpha_i x_i - \alpha_i(\gamma_i x_i + \kappa_i),$$

and the solution will satisfy

$$B_i'(x_i) = \alpha_i(1 + \gamma_i). \tag{9}$$

Comparing this first-order condition with (4) shows how the positive relationship between x_i and $\tilde{X}_{-i}$ means that a country will internalize more than the DSCC when setting its own emissions policy. The presence of $\alpha_i\gamma_i$ on the right-hand side reflects the additional, marginal disincentive to increase emissions: the expectation that other countries will increase their emissions too—by γ_i at a cost of α_i. The result is an effective subsidy on a country's emission reductions because other countries will reduce theirs as well.

There is also an important knife-edge result where a country will take account of exactly the GSCC. If $\gamma_i = A_{-i}/\alpha_i$, then expression (9) is equivalent to (2) for country i. In other words, if a country expects a decrease in its own emissions to decrease that of all others in proportion to the ratio of its external cost of emissions to its internal costs, then it is individually rational for the country to internalize the GSCC. Moreover, if the expectation were to hold for all i, then all countries would internalize the GSCC, and global emissions would be efficient.[11]

There are, however, some well-known shortcomings of the conjectural variations approach. The most obvious is that a country's conjecture is arbitrary and possibly incorrect. But this criticism should be considered in light of the fact that the assumption of Nash behavior can also be interpreted as quite arbitrary and perhaps more questionable in the context of international climate policy, where some degree of reciprocity

policy. Hahn and Ritz (2014) consider the role of altruism and find limited scope for countries to internalize the GSCC.

10. The approach here is based on that in Cornes and Sandler (1984, 1985) for public goods more generally.

11. Consider a special case where $n = 2$ and $\alpha_i = \alpha$ for $i = 1, 2$. It follows that a conjecture of $\gamma_i = 1$ means that both countries internalize $A = 2\alpha$, and the resulting levels of emissions are Pareto optimal.

among countries is clearly at work. Indeed, many countries promise emission reductions under the assumption that other countries will do the same. There are also concerns about whether conjectures are consistent with optimal responses at an equilibrium (Sugden 1985; Scafuri 1988), but these concerns reflect a more general criticism. Because conjectural variations are based on the idea that agents (i.e., countries) respond to one another in some particular way, arguments are often made that capturing the underlying idea is more appropriate through explicit modeling of a repeated game.[12]

4.2. A Repeated Game

International negotiations to mitigate climate change clearly have a repeated game aspect whereby countries set emission targets period after period.[13] As mentioned previously, the one-period game can be interpreted as a single long period, but in this subsection, I extend the model to a repeated game. To keep things as simple as possible, I consider only pure and stationary strategies, denoted as either $(x_1, \ldots, x_n)$ or $(x_i, \mathbf{x}_{-i})$ in more compact notation. All countries are assumed to have the discount factor $\delta \in (0, 1)$, complete information, and perfect recall of the history of play.

Assuming either an infinitely repeated game or one with an uncertain duration,[14] the discounted payoff to country i can be written as

$$\begin{aligned} V_i(x_i, x_{-i}) &= \sum_{t=1}^{\infty} \delta^{t-1}[B_i(x_i) - \alpha_i(x_i + X_{-i})] \\ &\approx \frac{1}{(1-\delta)}[B_i(x_i) - \alpha_i(x_i + X_{-i})] \\ &= \frac{v_i(x_i, \mathbf{x}_{-i})}{1-\delta}. \end{aligned} \tag{10}$$

A standard and immediate result is that the Nash equilibrium level of emissions in the stage game for all countries, $(\hat{x}_1, \ldots, \hat{x}_n)$, constitutes a subgame perfect equilibrium in the repeated game, and this result holds for any δ and prior history of emissions. This is consistent with all countries choosing to internalize the DSCC in the repeated game.

I now consider whether the choice of something greater than the DSCC—in particular, the GSCC—can be sustained as a subgame perfect equilibrium. A natural place to begin is with a Nash reversion strategy. All countries choose a level of emissions

12. Itaya and Okamura (2003) show specific cases in which the conjectural variations equilibrium is observationally equivalent to the strategies played in the subgame perfect equilibrium of the underlying repeated game for voluntary provision of a public good.

13. See Barrett (1994, 2003) for some of the early treatments and discussion of international environmental agreements as a repeated game.

14. In a game of uncertain duration, δ represents the product of the discount factor and the continuation probability. I will, however, refer to δ simply as the discount factor in the main text.

$(x_1, \ldots, x_n)$ in each period until one country deviates, at which point all countries revert to $(\hat{x}_1, \ldots, \hat{x}_n)$ for all periods thereafter. Whether continually choosing $(x_1, \ldots, x_n)$—and therefore an implied SCC for each country—constitutes a subgame perfect equilibrium depends on whether any country has an incentive to deviate in any period. The necessary and sufficient condition to avoid deviation can be written as

$$v_i(\hat{x}_i, \mathbf{x}_{-i}) - v_i(x_i, \mathbf{x}_{-i}) \leq \delta[V_i(x_i, \mathbf{x}_{-i}) - V_i(\hat{x}_i, \hat{\mathbf{x}}_{-i})] \text{ for all } i. \tag{11}$$

The left-hand side is the maximum gain from deviating in one period, and the right-hand side is the discounted future losses from reversion beginning in the next period. Substituting (10) into (11) and rearranging yields a useful variant of the same relationship:

$$\frac{1-\delta}{\delta}[v_i(\hat{x}_i, \mathbf{x}_{-i}) - v_i(x_i, \mathbf{x}_{-i})] \leq v_i(x_i, \mathbf{x}_{-i}) - v_i(\hat{x}_i, \hat{\mathbf{x}}_{-i}). \tag{12}$$

The left-hand side is always nonnegative and converges to zero as $\delta \rightarrow 1$. Hence whether the condition can be satisfied depends on whether the right-hand side is positive. This simple observation produces several results.

The first is that choosing to internalize more than the DSCC can be individually rational for all countries if δ is sufficiently large. To prove this, let $x_i = \hat{x}_i + dx$ for all i. It follows that $d\hat{v}_i/dx = \alpha_i(1-n) < 0$, and the right-hand side of (12) is positive for all i if $dx < 0$. This means that continually choosing $(x_1, \ldots, x_n) < (\hat{x}_1, \ldots, \hat{x}_n)$ is a subgame perfect equilibrium if δ is sufficiently close to 1. In other words, if countries care enough about the future, then in the repeated game, it is individually rational to emit less than the Nash equilibrium in the stage game, and this is equivalent to internalizing more than the DSCC.[15] While this may not be the first-best solution, the point is that countries are no longer stuck with only their DSCCs in the repeated game.

The second set of results relate specifically to the GSCC. If, as discussed in section 3, it holds that $v_i^* \geq \hat{v}_i$ for all i, and δ is sufficiently large, then $(x_1^*, \ldots, x_n^*)$ constitutes a subgame perfect equilibrium. Hence choosing to internalize the GSCC can be individually rational. Moreover, even if $v_i^* < \hat{v}_i$ for some i, transfers of the form defined previously, where $v_i^* - \hat{v}_i + \tau_i > 0$ for all i, can also support internalizing the GSCC in a repeated game. The overall intuition for these results is that if countries are concerned about the future and interact repeatedly, they will choose long-term cooperation over short-term gain.

There are many results applicable here from the literature on repeated games and the folk theorem. I have used what is perhaps the simplest setup to potentially rationalize a country's internalization of the GSCC, or at least something greater than the DSCC. The results highlight the importance of repeated interaction, complete in-

15. This result is essentially an application of the Nash reversion folk theorem (see Mas-Colell et al. 1995).

formation, and the potential use of transfers. It may be no coincidence therefore that each of these conditions featured prominently in the most recent United Nations Framework Convention on Climate Change (UNFCCC) agreement in Paris. The agreement has detailed provisions about the schedule for renewed commitments, mechanisms to improve information acquisition and dissemination, and commitments for climate finance to developing countries.

A promising line of future research is to consider alternative punishment schemes to Nash reversion, thereby allowing the study of more general insights of folk theorem type results.[16] Further research would also be useful that considers the effect of imperfect monitoring. Mailath and Samuelson (2006) provide a good starting point with their treatment of public and private monitoring, which in this case would capture realistic challenges for monitoring and reporting of emissions data through multilateral entities or countries themselves.

5. A COUNTRY'S PREFERRED SCC

With the exception of the choice of a discount rate in IAMs, empirical estimates of the GSCC are generally understood to be the result of positive rather than normative analysis. The existing research focuses on improving empirical methods and expanding data availability to provide better estimation (Pizer et al. 2014; Burke et al. 2016). Within a political context, however, seeking the one right estimate of the GSCC fails to recognize the heterogeneous incentives on the part of sovereign countries. Even with a true GSCC, countries will in general have different preferences for a globally internalized shadow value on emissions. In this section, I introduce the notion of a preferred SCC (PSCC) to define the concept. I then relate the PSCC to the other SCC measures and consider empirical evidence and policy implications.

One way to think about the approach is to consider each country's preference for the level of a uniform and globally implemented carbon tax, where each country retains its own tax revenue. The problem is similar to that in Weitzman (2014, 2015) but differs because the focus here is not on a carbon tax per se. Instead, I focus on the level of global ambition each country would like to see through a uniformly applied marginal cost on emissions, which can be implemented in countries through any choice of policy instruments.[17]

It is helpful to recognize that the approach taken here is an implicit burden-sharing agreement. The assumption is that all countries will adhere to a uniform shadow value on emissions, and country-specific demand functions determine the level of emissions

16. Although Nordhaus (2015) considers a static game, his formulation of a climate club that imposes trade sanctions on nonmembers provides an example of such a punishment scheme. See Böhringer et al. (2016) for an analysis with similar elements.

17. See Aldy and Pizer (2016) for a discussion on comparing ambition based on explicit and implicit carbon prices.

in each. There are, however, an infinite number of other possible burden-sharing agreements, and I do not model the decision about whether a country would voluntarily agree to the particular institutional arrangement. Instead, my approach is like that in Weitzman (2014, 2015), where commitment to the globally uniform shadow value (or tax, in his case) is assumed. The case is compelling here because of the focus on trying to understand the potential for international agreement on a single value of the global SCC.[18]

Let s denote a minimum marginal cost on emissions that all countries internalize. We can then write each country's associated level of emissions as

$$x_i(s) = \left\{ x_i : \begin{array}{l} B_i'(x_i) = s \;\text{ if }\; s \geq \alpha_i \\ B_i'(x_i) = \alpha_i \;\text{ otherwise} \end{array} \right\}.$$

This expression is equivalent to each country's demand for emissions with a price floor at its DSCC, reflecting how a country would choose to internalize α_i rather than some $s < \alpha_i$.

It follows that each country's preference for the uniformly implemented marginal cost of emissions comes from solving

$$\max_{s_i} B_i(x_i(s_i)) - \alpha_i \sum_{j=1}^{n} x_j(s_i). \tag{13}$$

Note that α_i is the only marginal damage that matters from country i's perspective. The solution to (13), denoted $\tilde{s}_i$, will satisfy

$$B_i'(x_i(\tilde{s}_i))x_i'(\tilde{s}_i) = \alpha_i \sum_{j=1}^{n} x_i'(\tilde{s}_i). \tag{14}$$

The important feature about this condition is that the right-hand side includes the avoided marginal damages to country i of lower emissions in country i and all other countries.[19] We can thus define the following:

Definition 3 (PSCC): The preferred social cost of carbon is $\tilde{s}_i$ for all i.

18. The need for countries to reach such an agreement already exists in multilateral financial institutions, such as the World Bank, where voting countries must decide on a value for the SCC to incorporate in program evaluation. In 2015, the World Bank practice was to use a value of $30 per ton, rising to $80 per ton by 2050 (World Bank 2015).

19. I have implicitly assumed that the second-order condition for a global maximum is satisfied. A sufficient (though not necessary) condition that I will use to illustrate some results is for all countries to have linear demand for emissions. This means that $x_i''(s) = -B_i'''(x_i(s))x_i'(s)/B_i''(x_i(s))^2 = 0$, which implies $B_i'''(x_i(s)) = 0$. It also implies that (13) is globally concave, as the second derivative of the objective function simplifies to $x_i'(s_i) < 0$.

I now consider how a country's PSCC compares with its DSCC and the GSCC, before turning to some empirical evidence and various decision rules for aggregating preferences.

5.1. Comparison with DSCC and GSCC

Let us first consider the DSCC. Rearranging (14) and using (4), we have

$$\begin{aligned} B_i'(x_i(\tilde{s}_i)) &= \alpha_i + \frac{\alpha_i}{x_i'(\tilde{s}_i)} \sum_{j \neq i} x'_j(\tilde{s}_i) \\ &> \alpha_i = B_i'(\hat{x}_i) = B_i'(x_i(\alpha_i)). \end{aligned}$$

Because $B_i''(x_i) < 0$, it follows that $x_i(\tilde{s}_i) < x_i(\alpha_i)$ and therefore $\tilde{s}_i > \alpha_i$. This implies that a country would choose a uniformly internalized marginal cost on emissions higher than α_i; that is, its PSCC is greater than its DSCC. The reason follows immediately from the comparison between (4) and (14): when choosing $\tilde{s}_i$, a country enjoys the additional benefit of "forcing" other countries to lower their emissions, and this provides an incentive to increase the domestically internalized cost beyond α_i.[20]

Turning now to a comparison with A, it is useful to begin with all identical countries. Recognizing the symmetry of solutions and suppressing subscripts, equation (14) simplifies to

$$B'(x(\tilde{s})) = \alpha n = A.$$

The immediate implication is that $\tilde{s} = A$. In other words, with all identical countries, each country would choose a PSCC equal to the GSCC, and as we have seen, this is consistent with globally efficient emissions.

But the same result does not hold in general with heterogeneity among countries. To see the different mechanisms at work, let us make the further simplifying assumption of linear demand for emissions in each country. Letting $x_i'(s) = b_i$ for all i, we can rewrite and simplify (14) as

$$B_i'(x_i(\tilde{s}_i)) = \alpha_i + \frac{\alpha_i}{b_i} \sum_{j \neq i} b_j. \tag{15}$$

The general result is that each country's choice of $\tilde{s}_i$ can be greater than or less than A. This follows immediately from (15) because the right-hand side does not depend on α_j for all $j \neq i$, which gives wide latitude for the second term to be greater than or less than A_{-i}.

20. Weitzman (2014) discusses an externality internalizing incentive in the context of a uniformly applied carbon tax, but the idea has an earlier provenance in public economics (Bowen 1943), where, for example, there is concern about tax rates that citizens in a municipality would like to see for the provision of public goods such as education. Individuals are willing to pay higher taxes themselves in order to get the benefit of others having to do the same.

To build intuition for the different possibilities, it is useful to consider the simple case where $n = 2$. If we simplify even further by assuming $b_i = b_j$, it is easy to see from (15) that $\tilde{s}_i \gtreqless A(= \alpha_i + \alpha_j)$ if and only if $\alpha_i \gtreqless \alpha_j$. This implies not only that a country with greater marginal damages chooses a greater PSCC; a country's PSCC will be greater than the GSCC when it has relatively higher marginal damages. In this case, there is an incentive to force the other country to lower emissions, with overall reductions more than are efficient. It is also useful to consider the case of $\alpha_i = \alpha_j$ and heterogeneous demand, whereby $\tilde{s}_i \gtreqless A$ if and only if $b_j/b_i \gtreqless 1$, and recall that $b_i, b_j < 0$. This means, for example, that country i will choose a PSCC greater than the GSCC if and only if country j has a more responsive demand for emissions. The reason is that country i does not experience the greater marginal cost of forgone emissions in country j when determining its preference for a uniform marginal cost on emissions.[21]

In summary, all countries will have a PSCC greater than their own DSCC, but possibly greater than or less than the GSCC. The fact that some countries may prefer a uniform marginal cost of emissions greater than the GSCC is at first somewhat counterintuitive but becomes clear when considering how these are countries with relatively flat demand for emissions, large marginal damages, or both. These are in effect the countries that would like to see a very stringent global emissions policy, a view certainly consistent with those of the small island nations. In these countries, the costs of abatement may be relatively low, but the benefits to them of worldwide abatement are very high. In particular, benefits from the amount of abatement that a high PSCC would induce in other, larger countries could easily offset the increase in a small island nation's own abatement costs.

5.2. Empirical Evidence and Decision Rules

I now provide some empirical evidence on the PSCC for different countries and regions using the C-DICE model (Nordhaus 2015). Consistent with the parameterization discussed in section 3, I assume a GSCC of \$40, the distribution of DSCCs shown in figure 1, and benefit functions described in note 9. Figure 3 lists the PSCC for each country or region. They range from a low of \$13 for Eurasia to a high of \$91 for India. The countries and regions are almost evenly split between those with a PSCC below and above the GSCC of \$40. Figure 3 also illustrates single-peaked preferences for the PSCC graphically: each country or region's net benefit (normalized to its maximum at the PSCC) is shown on a curve for different levels of a globally internalized shadow value on emissions. These curves show how preferences (i.e., net benefits) for the PSCC

21. A further result worth noting with linear demand is the possibility for $\tilde{s}_i = A$ for all i even with heterogeneous countries. Although it is a knife-edged result, the condition will hold if all countries have the same ratio of marginal costs to benefits of emissions; that is, the ratio α_i/b_i is the same for all i. To see this, note that the identical ratio condition requires $b_j = b_i(\alpha_j/\alpha_i)$ for all j and i, and substitution into (15) yields a right-hand side equal to A.

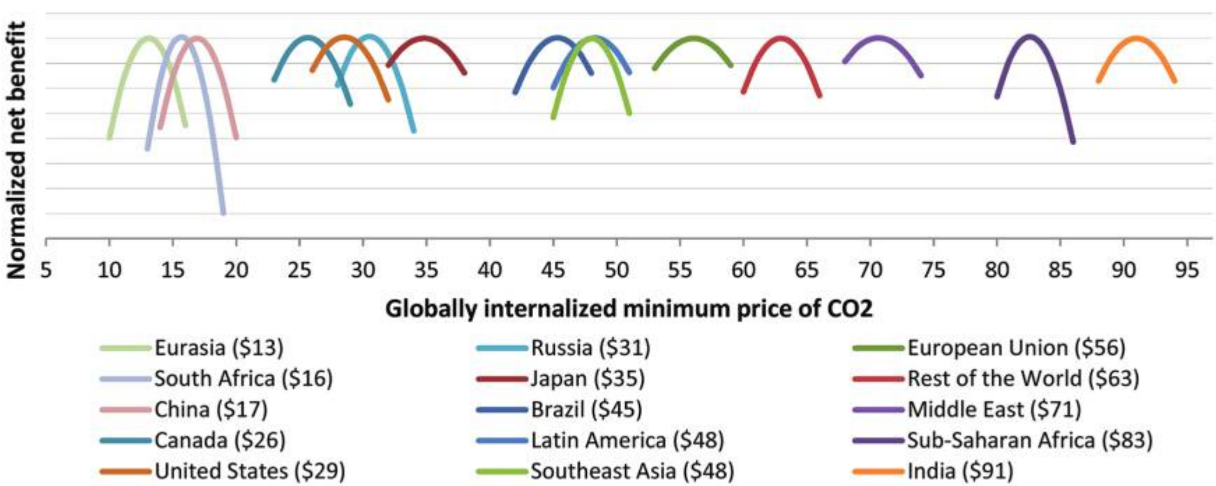

Figure 3. Single-peaked preferences for the PSCC for countries or regions, given a GSCC of $40

Table 1. Decision Rules and Corresponding Outcomes for the Decision Cost of Carbon (DCC)

Decision Rule	Outcome DCC ($)	Mean PSCC ($)
Majority voting	45	44.8
Population weighted	51	54.6
GDP weighted	46	45.3
Unanimity (Nash reference)	21	

Note. Dollar amounts are per ton, and the GSCC is set at $40.

have a unique maximum; that is, a country or region's net benefit declines as the shadow price moves away from its optimal PSCC in either direction.

To gain intuition about the heterogeneity of results, it is helpful to refer back to panel B of figure 2. Notice that those with greater benefits of moving to globally efficient emissions tend to be those with a higher PSCC. Indeed, these are the countries/regions with a relatively high DSCC and low marginal abatement costs, while also taking account of how responsive other countries are to changes in the shadow value of emissions.

The set of preferences illustrated in figure 3 provides a basis for studying how countries might agree on a uniformly implemented shadow value on emissions. Weitzman (2014, 2015) considers a thought experiment involving a fictitious World Climate Assembly that votes on a uniform carbon tax. But the need for such preference aggregation can apply more generally to a globally internalized shadow price, regardless of the policy instrument. This might arise as part of an international agreement, where, for example, Aldy and Pizer (2016) discuss benchmarking levels of ambition based on implicit prices of carbon.

As mentioned previously, I assume that countries must agree on a single, minimum SCC that all countries internalize. Let $\mathcal{D} : \mathcal{R}^n \rightarrow \mathcal{R}^1$ denote a decision rule that maps n country preferences for the PSCC into a single number, denoted DCC for decision cost of carbon. I consider several voting rules to study how they affect the DCC.[22]

Table 1 lists the different rules and corresponding estimates of the DCC. Recall that the analysis takes place with the underlying assumption of a true GSCC equal to $40. The natural starting point is majority voting, for which the standard result is that the outcome will reflect preferences of the median voter. In this case, the median voter is Brazil, and the DCC is $45. As a point of comparison, the table also reports the mean PSCC corresponding to each voting scheme, and in all cases, the mean is close to the median. Other voting schemes are a population weighted majority at $51, and a GDP

22. In all cases, I apply the decision rule under the assumption of no transfers from one country to another.

weighted majority at $46. Given the way that UNFCCC decision making is based on consensus, I also consider the largest shadow value that would achieve unanimous support in the sense that no country would prefer the Nash equilibrium. The result is $21, and the pivotal region is Eurasia. A noteworthy finding is the way that the different voting schemes tend to result in a DCC quite close to the GSCC.

6. CONCLUSION

This paper contributes a theoretical foundation for the SCC to a literature that focuses almost exclusively on producing empirical estimates. The basic framework highlights the distinction between the DSCC and the GSCC, and relates them to the conditions of Pareto optimality and Nash equilibrium for a global public bad. The model helps frame the growing debate about whether countries should take account of the global benefits of reducing greenhouse-gas emissions when setting and evaluating domestic policy. At its core, from a static perspective, the distinction relies on a determination of the appropriate extent of a market for efficient provision of a global public good. Analysis also shows how choices between the DSCC and the GSCC are subject to distributional effects in addition to well-known free riding incentives.

Extensions of the model identify conditions under which a country's decision to internalize the GSCC, or at least something greater than the DSCC, can be individually rational. To capture international relations where a country reduces its own emissions to leverage reductions from other countries, I consider non-Nash behavior with a conjectural variations approach. As another alternative, I extend the model to a repeated game that accounts for the way international negotiations to mitigate climate change take place repeatedly over time. Folk theorem type results prove useful in this context. In both cases, it can be in a country's self-interest to internalize the GSCC. The results should help inform ongoing debate about the appropriate scope of the SCC in domestic policy analysis. Indeed, the debate has moved front and center in the United States because of the differing approaches between the Obama and Trump administrations for using the SCC in regulatory impact analysis.

But countries may not agree on the same value of the GSCC, and understanding why is consistent with the notion of the preferred SCC that I develop here. Seeking one estimate of the GSCC upon which all sovereign countries can agree abstracts from each country's heterogeneous incentives. I show how all countries have a PSCC that is greater than their DSCC but can be less than or greater than the GSCC. Empirical evidence based on the C-DICE model shows how countries or regions would prefer a globally internalized shadow value on emissions that ranges from $13 (Eurasia) to $91 (India) when the actual GSCC is $40. Different voting schemes for preference aggregation, however, result in shadow values relatively close to the GSCC.

In conclusion, this paper shows how establishing and using the GSCC among sovereign countries is not simply a case of estimating and internalizing an externality. While the theoretical treatments and empirical demonstrations are intentionally simple, they open the door to future research with potentially important insights to guide the estimation and use of the SCC and to inform the design of future climate policy.

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