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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, as currently practiced in the United States, is individually rational. Nevertheless, I show how obtaining international consensus on a particular value will be more challenging than often appreciated. I introduce the notion of "strategic SCC" 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 strategic SCC greater than their domestic SCC, a country's strategic 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. A central contribution of the paper is demonstration of the need for more research on the theoretical underpinnings of the SCC for policy analysis, because establishing and using the SCC among sovereign countries is not simply an application of estimating and internalizing an externality.

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1 Introduction

Individual agents across the planet have little or no incentive to internalize the global costs of their own climate-changing emissions. From this perspective, 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—the United States, Canada, Finland, France, Germany, Italy, Mexico, Netherlands, Norway, and the United Kingdom—have begun accounting for the SCC in regulatory impact analyses of domestic policy. In doing so, these countries take into account the *global* benefits of reducing CO_2 emissions (i.e., avoided damages worldwide) when conducting benefit-cost analyses of *domestic* regulations.[1]

There is, however, growing debate about whether the global SCC is appropriate for benefit-cost analysis of domestic policy. The practice is 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; Gayer and Viscusi 2015; Darmstadter 2016; Fraas *et al.* 2016). 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 (mis)allocation of societal resources.[2] Questions

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[1] Currently, the United States uses a central estimate of \$40 per metric ton of CO_2 emitted in 2015 (in 2014\$s), with increasing numbers for each year thereafter (Interagency Working Group 2013). In an important application of the SCC, the U.S. Environmental Protection Agency (EPA) estimates global benefits of \$20 billion per year by 2030 from the Clean Power Plan to regulate emissions from existing power plants (U.S. EPA 2014).

[2] Aldy (2015) provides a useful discussion about the importance of the SCC for both implementing and evaluating climate policy.

also arise about consistency with individual rationality (i.e., self interest) from any one country's perspective.

Despite the widespread use of the SCC for evaluating climate policy, and the emerging 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 also show how obtaining international consensus on a particular value of the global SCC will be more challenging than often appreciated.

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. A useful feature of the model is the way it clarifies how emissions produce a global externality from the perspective of individual agents, but a global public bad from the perspective of countries. Analysis in Section 3 shows how internalizing the global SCC is consistent with Pareto optimality 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 4 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 5 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 among countries 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 emission 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, the SCC is generally perceived as an objective parameter, the estimates of which are limited primarily by empirical methods and data availability.[3] For political purposes, however, seeking the one right estimate of the global SCC fails to recognize strategic incentives on the part of countries. In Section 6, I introduce the notion of "strategic SCC" to reflect each country's preference for a globally internalized shadow value on emissions conditional on a true value of the global SCC and on a distribution of the domestic SCCs among countries. While all countries have a strategic SCC greater than their domestic SCC, a country's strategic SCC 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. I also discuss immediate implications of the results for debates currently underway in multilateral institutions, such as the World Bank, about how to account for climate-change impacts in program evaluation.

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. This builds support for current practice in the United States and other countries. 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.

2 The Model Setup

I construct the simplest model possible to illustrate the key ideas. Countries are indexed $i = 1, ..., n$ with $n \geq 2$. Each country has emissions x_i, and the initial

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[3] With the exception of necessary (and important) assumptions about the discount rate, we might consider estimates of the SCC to be the result of positive rather than normative analysis.

version of the model is static.[4] The aggregate level of emissions, $X = \sum_{i=1}^{n} x_i = x_i + X_{-i}$, 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 $B_i''(x_i) < 0$.

A few observations are useful about the country-level specification of 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 social cost of carbon:

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* $A = \sum_{i=1}^{n} \alpha_i$.

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, 2015), they provide the leading approach among researchers and policymakers for estimating the GSCC (Metcalf

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[4] 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 5.2.

and Stock, 2015). Indeed, the U.S. estimates of the GSCC used in regulatory impact assessment are based on a synthesis analysis of three different IAMs (Interagency Working Group 2013).[5] The central estimate of the GSCC, based on a 3-percent discount rate, is \$40 (in 2014\$s) per metric ton of CO_2 emitted in 2015, with the number increasing in future years.

As the IAMs have become more detailed over time, greater efforts have been made to increase 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 distribution of the GSCC by region, no one region or country appears to dominate the total. Subsequently, Nordhaus (2015) merges the results to derive a regional decomposition of the GSCC based on an average of three models.[6] I report the distribution in Figure 1 to provide a sense of the empirical heterogeneity in the DSCC, recognizing that some estimates are for regions rather than countries. The estimates range from nearly 14 percent of the GSCC for the European Union to less than 1 percent for South Africa. The figure also illustrates how the percentage distribution partitions the GSCC of \$40 among different countries or regions.[7] For example, the United States share is about \$4.24. Across the distribution, Nordhaus (2015) observes that the estimates are roughly proportional to discounted Gross Domestic Products (GDPs), with deviations based on geographic differences in climate sensitivity.

3 Efficiency *vs.* 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. I begin with globally 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

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[5] The three different models are DICE, FUND, and PAGE. Detailed reference information is available in the Interagency Working Group report.

[6] See Table B-2 in the Online Appendix in Nordhaus (2015)

[7] 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 the same percentages hold for a GSCC of \$40.

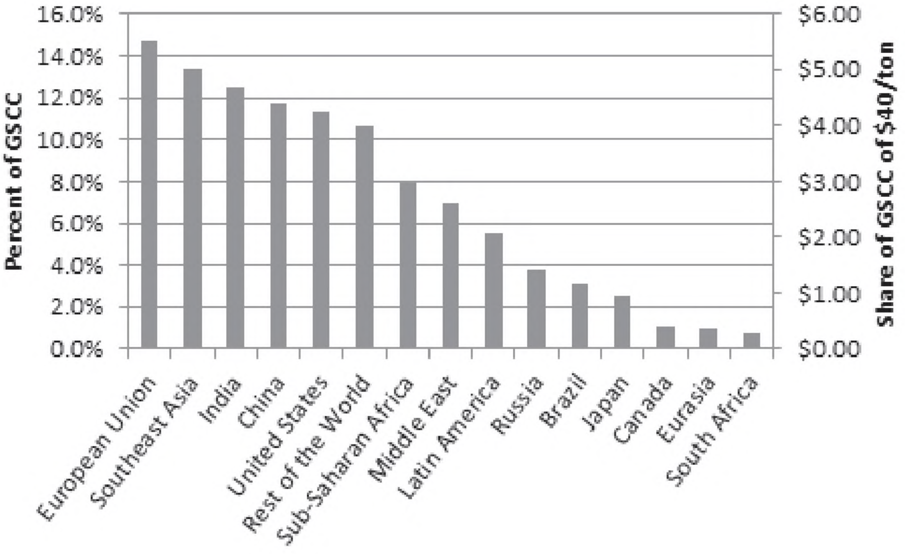

Figure 1: Heterogeneity in the distribution of the GSCC across countries or regions based on averaging across three IAMs

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 $s_i = p_i$.

3.1 Pareto Optimality

Pareto optimality in global emissions must maximize aggregate surplus. The efficiency objective is to coordinate the internalized, shadow value of emissions among all countries to solve

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

Assuming an interior solution (here and throughout), the conditions that define the solution $(s_1^*, ..., s_n^*)$ can be combined as follows:

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

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. 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, $X^* = \sum_{i=1}^{n} x_i^*$. This, of course, is the efficiency argument in support of all countries internalizing the GSCC for domestic policy.

Although a bit of an aside, it is worth pointing out that the efficiency conditions in (2) are related to, and yet distinct from, the standard condition for optimal provision of a public good (bad). The classic Samuelson condition would equate the sum of the marginal benefits of reducing the public bad to the marginal costs of doing so. In this case, the sum of the marginal benefits corresponds to A, but, in contrast to the Samuelson condition, these marginal benefits equal the marginal costs of reducing emissions (foregone benefits) in all countries, which themselves must all be equal. The difference arises here because the marginal costs of abatement come from sources within each country separately rather than from a uniform price or market supply curve. This is why there are n conditions in (2) rather than the single Samuelson condition.

3.2 Nash Equilibrium

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

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

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 $\hat{s}_i$ will solve

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

		Country A	
		DSCC$_A$	GSCC
Country B	DSCC$_B$	2 , 2	4 , 1
	GSCC	1 , 4	3 , 3

Figure 2: Example where the choice of the DSCC over the GSCC is consistent with a classic prisoners' dilemma

In this case, each country's demand for emissions implies that $\hat{s}_i = \alpha_i$ for all i.[8] 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 $\hat{X} = \sum_{i=1}^{n} \hat{x}_i$.

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.

It is worth noting that the characterization of a global public bad differs somewhat from a global externality, and this is due the level of analysis taking place among countries rather than individuals. The standard definition of an externality means that agents take no account of any external damages of their actions. But here each country experiences some of the marginal damages from its *own* emissions, in addition to damages from the emissions of other countries. This explains why countries will, to some extent, constrain their own equilibrium emissions with a choice of $s_i > 0$, rather than $s_i = 0$, which would have emissions increase until $B_i'(x_i) = 0$. Nevertheless, individual agents within each country do not have such an incentive because they experience an infinitesimally small fraction of damages from their own emissions.

Figure 2 illustrates the idea of free riding on abatement in the form of a

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[8] Notice 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.

		Country A	
		DSCC$_A$	GSCC
Country B	DSCC$_B$	3 , 1	5 , 0
	GSCC	0 , 5	2 , 4

Figure 3: Example where Pareto optimality of internalizing the GSCC is not a Pareto improvement

classic prisoners' dilemma. There are $n = 2$ identical countries, and each faces the choice of internalizing its DSCC or the GSCC. In this example, both countries are better off if they both choose the GSCC (the Pareto optimal solution), but doing so is not a Nash equilibrium. The payoffs are such that both countries have a dominant strategy to choose the DSCC, resulting in a Nash equilibrium where both countries obtain a lower payoff.

4 Distributional Considerations

It is well recognized that the globally efficient level of emissions is not an equilibrium. Generally less well known is that all countries would *not* necessarily prefer the efficient level of emissions, even if it could be sustained. Figure 3 modifies the payoffs to the prisoners' dilemma to illustrate a simple example. Pareto optimality occurs if both countries choose the GSCC, were the combined payoffs are maximized, but the Nash equilibrium still occurs when both countries choose their respective DSCC. The difference arises now because Country B is actually worse off at the Pareto optimal outcome compared to the Nash equilibrium. Without a transfer from Country A to Country B (of at least one unit of payoff), the problem is one of distribution in addition to free riding.

I now consider more generally the potential distributional effects upon moving from equilibrium to efficient emissions. Let us 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 is that of all identical countries because the efficient level of emissions will always Pareto dominate the equilibrium. By

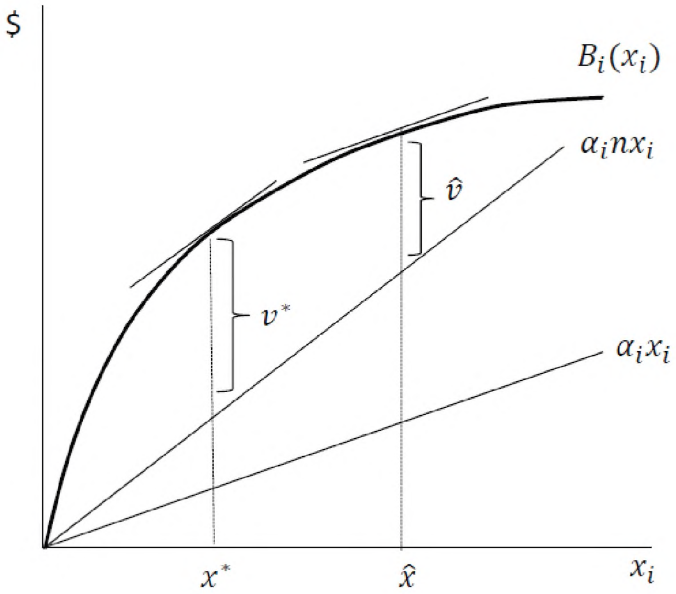

Figure 4: A country's net benefits at Pareto optimal and Nash equilibrium emissions with n identical countries

symmetry, each country will have 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

$$\begin{aligned} v^* - \hat{v} &= [B(x^*) - \alpha n x^*] - [B(\hat{x}) - \alpha n \hat{x}] \qquad (5) \\ &= \alpha n(\hat{x} - x^*) - \int_{x^*}^{\hat{x}} B'(z)dz > 0, \qquad (6) \end{aligned}$$

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 foregone benefits of further reducing its own emissions (the second term). Figure 4 illustrates the result graphically. The result is also 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 heterogenous countries. The more general formulation of (5) and (6) for all i is

$$\begin{aligned} v_i^* - \hat{v}_i &= \alpha_i(\hat{X} - X^*) - \int_{x_i^*}^{\hat{x}_i} B_i'(z)dz & (7) \\ &= \underbrace{\alpha_i(\hat{X}_{-i} - X_{-i}^*)}_{>0} + \underbrace{\alpha_i(\hat{x}_i - x_i^*) - \int_{x_i^*}^{\hat{x}_i} B_i'(z)dz}_{<0}, & (8) \end{aligned}$$

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- or better-off upon moving to the globally efficient level of emissions, without transfers. The first 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 greater marginal damages from emissions 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 foregone benefit from reducing emissions. The net effect is always negative, and the magnitude is increasing in the size of the externality being internalized, A_{-i},which follows because $x_i^* \rightarrow \hat{x}_i$ as $A_{-i} \rightarrow 0$.

The more general concept underlying these different possibilities 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 $\sum_{i=1}^n v_i^* > \sum_{i=1}^n \hat{v}_i$ 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 internal setting. In particular, we know there exists a set of transfers $(\tau_1, ..., \tau_n)$ such that $\sum_{i=1}^n \tau_i = 0$ and $v_i^* - \hat{v}_i + \tau_i \geq 0$ for all i, holding strictly for at least some i.

Let us for the moment consider some simulation-based empirical evidence. I employ the basic set up 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

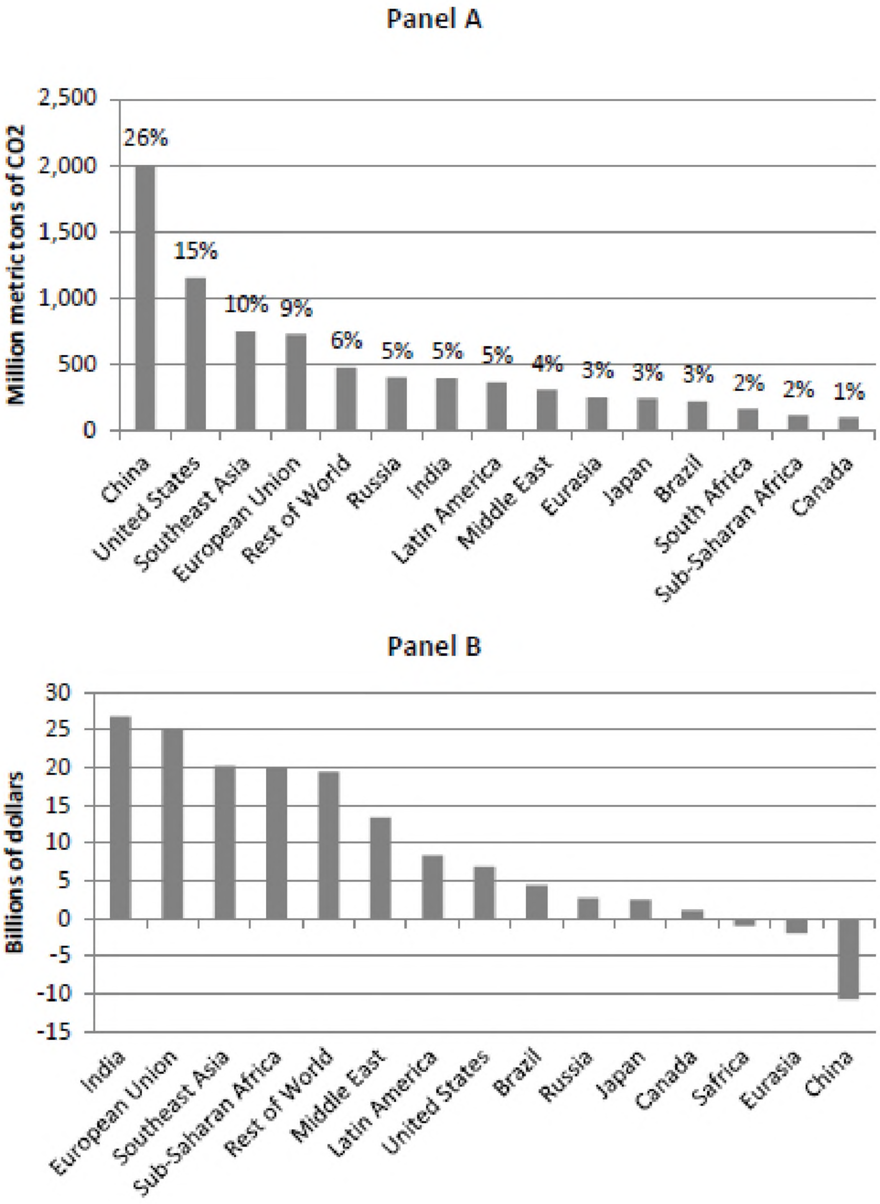

Figure 5: Simulated abatement of countries or regions (Panel A) and change in welfare (Panel B) of moving from equilibrium to Pareto optimal emissions without transfers

of \$40. The country benefits of emissions are based on the functional form and parameterization in Nordhaus (2015, Table B-4).[9] With this setup, I solve for equilibrium and Pareto optimal emissions for each country and report the results of interest in Figure 5. Panel A shows each country's abatement of moving from equilibrium to Pareto optimal emissions, i.e., $\hat{x}_i - x_i^*$. Overall emissions decline by 22 percent, and the figure shows the percentage of the total reduction attributable to each country. For example, 26 percent of the reduction comes from China and 9 percent 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. Clearly, the net benefits exceed costs across all countries.

5 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 model that reflect the real-world institutional context where climate policy and international negotiations take place can produce a different result. I do not claim that the models in the following two subsections are necessarily the right ones; rather, my aim is to illustrate simple possibilities that are consistent with observed policies and that can spur further theoretical research on this increasingly important, policy-relevant question.

5.1 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 affect on the emissions of other countries. But this assumption ignores the potential importance of

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[9] 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 $x_i \leq \bar{x}_i$.

international relations where some countries may reduce their emissions to leverage reductions from other 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. Here I consider the choices of x_i directly (rather than s_i) in order to simplify notation. The simplest way to characterize the 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 (increase) in its own emissions will decrease (increase) 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. 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 Pareto optimal.

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

It is worth briefly mentioning how the conjectural variations solution relates to other solutions for solving public goods problems. The most noteworthy is a Lindahl equilibrium. Although often discussed as pertaining to individualized prices for providing a public good, Lindahl's thought experiment can be motivated using quantities rather than prices (see, for example, Cornes and Sandler 1996). Assume that each country is permitted a share of global emissions, $\theta_i = x_i/X$, that is determined exogenously and $\sum_{i=1}^{n} \theta_i = 1$. A Lindahl equilibrium, which by definition implements Pareto optimal emissions, then arises if $\theta_i = \alpha_i/A$ for all i.[11] Differentiating the share equation, it holds that $dX_i/dx_i = (1-\theta_i)/\theta_i = \gamma_i$, so the difference between Lindahl shares (which also define an optimal burden-sharing agreement) and the conjectural variation parameter is therefore a matter of interpretation.

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 is also quite arbitrary and perhaps more questionable in the context of international climate policy, where some degree reciprocity among countries is clearly at work. 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]

5.2 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

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[11] To see this, solve $\max_{x_i}\{B_i(x_i) - \alpha_i X\}$, where $X = x_i/\theta_i$ and $\theta_i = \alpha_i/A$, to verify the solution is x_i^* for all i.

[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.

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 $(x_1, ..., x_n)$ 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

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

A standard and immediate result is that the Nash equilibrium level of emissions in the stage game for all countries, $(\hat{x}_1, ..., \hat{x}_n)$, 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 Nash reversion strategies. All countries choose a level of emissions $(x_1, ..., x_n)$ in each period until one country deviates, at which point all countries revert to $(\hat{x}_1, ..., \hat{x}_n)$ for all periods thereafter. Whether continually choosing $(x_1, ..., x_n)$—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

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

The left-hand side is the maximum gain from deviating in one period, and the right-hand side is the discounted future loses from reversion beginning in the next

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[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.

period. Substituting (10) into (11) and rearranging yields a useful variant of the same relationship:

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

The left-hand side is always non-negative and converges to zero as $\delta \to 1$. 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 $(x_1, ..., x_n) < (\hat{x}_1, ..., \hat{x}_n)$ 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 4, it holds that $v_i^* \geq \hat{v}_i$ for all i, and δ is sufficiently large, then $(x_1^*, ..., x_n^*)$ 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. It is worth mentioning that a common critique about the usefulness of the Folk Theorem is that "anything goes" because of the large set of potential subgame perfect equilibria in repeated games. In this setting, however, that is precisely the contribution, because it shows how countries choosing to internalize something more than their DSCC can be individual rational. 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.

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[15] This result is essentially an application of the Nash Reversion Folk Theorem (see Mas-Colell *et al.* 1995).

The results highlight the importance of repeated interaction, complete information, 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 and 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.

6 Strategic 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 strategic 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 strategic SCC (SSCC) to define the concept. I then relate the SSCC to the other SCC measures and consider empirical evidence and policy implications.

One way to think about the task at hand 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 that in Weitzman (2014, 2015), but differs because the focus here is not on a carbon tax *per se.*

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[16] Although Nordhaus (2015) considers a static game, his formulation of a climate club that imposes trade sanctions on non-members provides and example of such a punishment scheme. See Böhringer, Carbone, and Rutherford (2016) for an analysis with similar elements.

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]

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

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

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 a 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

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

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.[18] We can thus define the following:

Definition 3 (SSCC) *The* Strategic Social Cost of Carbon *is* $\tilde{s}_i$ *for all* i*.*

I now consider how a country's SSCC compares with its DSCC and the GSCC,

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

[18] 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 $x_i'(s_i) < 0$.

before turning to some empirical evidence and various decision rules for aggregating preferences.

6.1 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 SSCC is greater than it 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.[19]

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 SSCC equal to the GSCC, and as we have seen, this is consistent with Pareto optimal 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

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[19] Weitzman (2014) discusses an externality internalizing incentive in the context of a uniformly applied carbon tax, but the idea has a much 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 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.

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}.

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 SSCC; a country's SSCC 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 Pareto optimal. It is also useful to consider the case of $\alpha_i = \alpha_j$ and heterogenous 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 that country i will choose a SSCC greater (lower) than the GSCC if and only if country j has a more (less) responsive demand for emissions. The reason is that country i does not experience the greater (less) marginal cost of foregone emissions in country j when determining its preference for a uniform marginal cost on emissions.[20]

In summary, all countries will have a SSCC 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 counter-intuitive, 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.

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[20] A further result worth noting with linear demand is the possibility for $\tilde{s}_i = A$ for all i even with heterogenous 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.

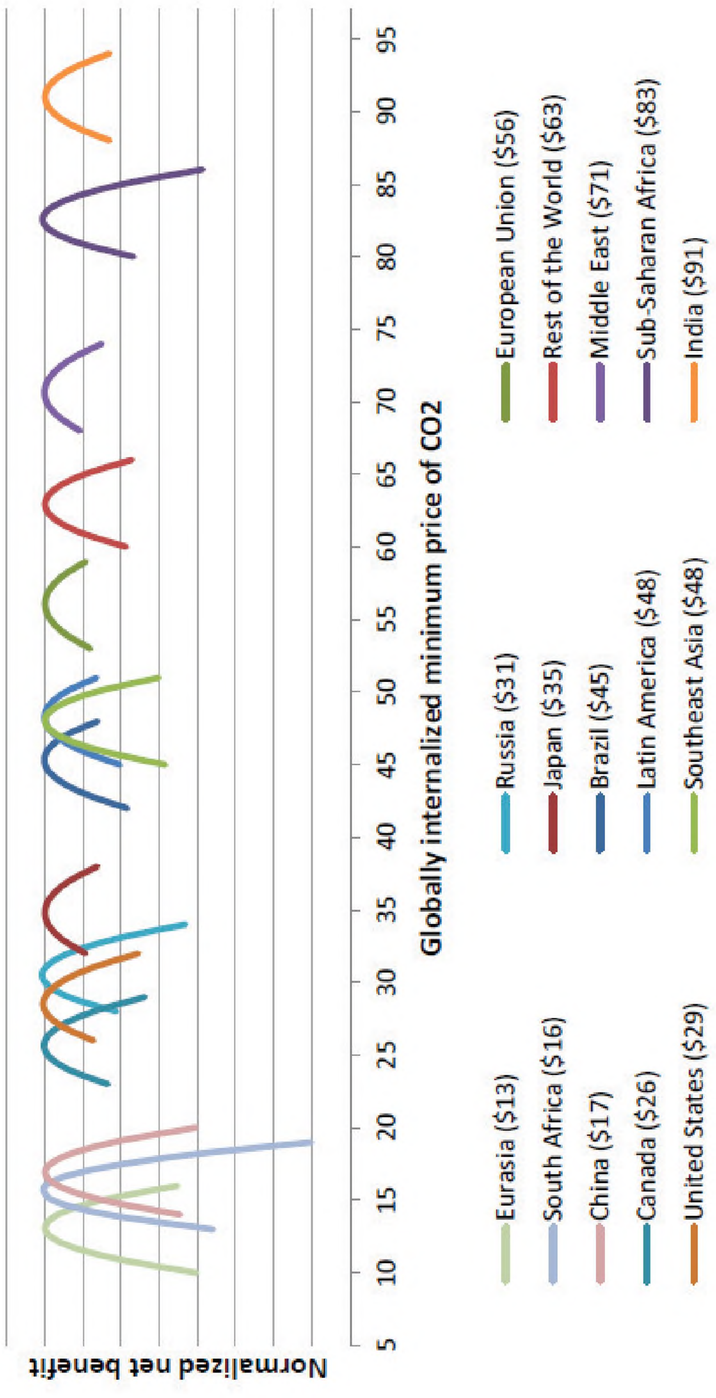

Figure 6: Single-peaked preferences for the SSCC for countries or regions, given a GSCC of $40

6.2 Empirical Evidence and Decision Rules

I provide some empirical evidence on the SSCC for different countries and regions using the C-DICE model (Nordhaus 2015). Consistent with the parameterization discussed in Section 4, I assume a GSCC of \$40, the distribution of DSCCs shown in Figure 1, and benefit functions described in footnote 9. Figure 6 lists the SSCC 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 SSCC below and above the GSCC of \$40. Figure 6 also illustrates preferences for the SSCC graphically. Each country or region's net benefit (normalized to its maximum at the SSCC) is shown on a curve for different levels of a globally internalized shadow value on emissions. These curves show how preferences for the SSCC are single-peaked; that is, a country or region's net benefit declines as the shadow price moves away from its preferred SSCC.

The set of preferences illustrated in Figure 6 provide 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. More immediately, multilateral development agencies, such as the World Bank, emphasize the need to account for a SCC in program evaluation that voting member countries must approve.[21]

In what follows, I assume 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 SSCC 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. The natural starting point is majority voting, for which the standard result is that the

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[21] The World Bank currently uses a value of \$30 per ton in 2015, raising to \$80 per ton by 2050 (World Bank 2015).

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

Table 1: Decision rules and corresponding outcomes for the DCC

Decision rule	Outcome DCC	Mean SSCC
Majority voting	\$45	\$44.8
Population weighted	\$51	\$54.6
GDP weighted	\$46	\$45.3
Unanimity (Nash reference)	\$21	
World Bank voting shares		
Intl Bank for Reconstruction and Devt (IBRD)	\$48	\$46.5
Intl Finance Corporation (IFC)	\$46	\$45.7
Intl Development Association (IDA)	\$54	\$50.2

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 SSCC 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 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. Finally, I consider voting outcomes weighted by actual voting shares of different units within the World Bank Group.[23] This results in \$48 for the International Bank for Reconstruction and Development (IBRD), \$46 for the International Finance Corporation (IFC), and \$54 for the International Development Association (IDA). In all cases, the number is higher than the \$30 currently used at the World Bank.

7 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 this 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

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[23] I use the voting power of each country as of March 2016. These data, along with the methods for deriving voting power, are available for all World Bank Units at http://www.worldbank.org/en/about/leadership/VotingPowers.

account of the *global* benefits of reducing greenhouse-gas emissions when setting and evaluating *domestic* policy. Analysis also shows how choices between the DSCC and the GSCC are subject to distributional effects in addition 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, as currently practiced in regulatory impact analysis by a growing number of countries.

But countries may not agree on the same value of the GSCC, and understanding why is consistent with the notion of a strategic SCC that I develop here. Seeking one estimate of the GSCC upon which all sovereign countries can agree abstracts from each country's strategic incentives. I show how all countries prefer a SSCC 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, a central contribution of this paper is demonstration of the need to more research on the theoretical underpinnings of the SCC. I have sought to show 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 inform the design of future climate policy.

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