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Regional variation, holdouts, and climate treaty negotiations

Abstract: We develop a model of international agreements to price a transboundry externality and provide a new heuristic to aid in interpreting negotiation behavior. Under conservative assumptions, a country's net benefits will be positive under an efficient pollution price if its share of global damages is less than half its share of worldwide abatement costs. We solve for a permit allocation scheme consistent with that heuristic such that every region will have positive net benefits in an agreement to price the pollution externality at the globally efficient level. We then apply this framework to climate change using regional data from Integrated Assessment Models and test the feasibility of a global climate change treaty. The results indicate that several regions have positive net benefits from a globally efficient price on carbon, including Western Europe, South Asia (including India), and Latin America. We then solve for a permit allocation scheme that should produce worldwide agreement on a climate treaty. Using the same model, we show that differential carbon taxes aimed at producing universal agreement would produce tax rate differences of an order of magnitude. We also argue that shares of global GDP might be an appropriate proxy for exposure to climate damages and find that a global climate treaty would be cost-benefit justified for all countries without transfers when that assumption is used.

Keywords: climate change; developing countries; international climate policy; transboundry pollution.

JEL classification: Q54; F51; H23

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1 Introduction

There are substantial obstacles to achieving efficient policy solutions to global externalities. In the best of circumstances, sovereign nations cooperate to produce (at least nominally) binding agreements. But negotiating these agreement is complicated by the strategic behavior of the parties, each seeking to maximize its own individual share of the net benefits. Internal political obstacles may also prevent countries from acting in the international arena even when it is in their own best interest. These strategic and public choice issues can delay, or even scuttle, agreement on international treaties that would generate large net benefits.

In this paper, we propose a new test to suss out which countries would experience positive net benefits under an agreement to internalize a global externality. The results can be used to separate parties that require a side-payment to join such a treaty from countries behaving strategically to secure unnecessary side payments or freeride off other countries' emissions reductions. Such a test would be useful in ensuring that welfare-enhancing efforts to reduce transboundry externalities are not waylaid by strategic action on the part of negotiators. To describe this test, we develop a stylized model of the costs and benefits of internalizing a global externality. The model can be used to estimate a country's net benefits based on *shares* of global costs and benefits rather than levels. This can be particularly useful when information about the shares of global costs and benefits is more readily available (or more certain) than estimates of total cost and benefit levels. We begin by modeling the conditions for net benefits of eliminating a global externality for a given country.

We use the model to describe a permit allocation scheme that would equate private and social cost while transferring wealth to countries with negative net benefits under the initial conditions. The wealth transfer takes the form of granting holdout countries permits in excess of their share of global emissions while reducing the allocation to countries that clearly benefit from internalizing the externality. We also use the model to illustrate the difficulties of using differential tax rates across countries.

We then use data on the distribution of climate change risks and greenhouse gas abatement costs to explore the model in the context of a specific global environmental externality. Using data produced by integrated assessment models (IAMs), we apply the simple test described above to identify countries that are extremely likely to be better off under a globally efficient climate treaty vis-à-vis the status quo and in the absence of transfers. We identify several global regions, including China and the United States, that might be holdouts to a climate treaty that prices greenhouse gas emissions at the efficient level.

We then solve for a permit allocation scheme that would ensure all global regions are incentivized to join a global climate change treaty that prices carbon at the social optimum. The results suggest that permit allocation to Western Europe and South Asia, including India, would be far below their share of global emissions (in the efficient emission pathway) and that additional permits ranging from 3.8% to 10% of global emissions would be allocated to China and the United States. Finally, we test the efficacy of schemes that would allow differential emissions tax rates across countries. Huge differentials in tax rates suggest that this would not be a cost effective scheme for reducing emissions to the efficient level.

There is a voluminous literature on the cost and benefits of controlling greenhouse gas emissions.[1] We focus on bringing together the strand of the literature that estimates the magnitude of damages under climate change [see Tol (2012), Weitzman (2010), and Nordhaus (2008) among many others] with the literature that examines international negotiations to address climate change [see Carraro and Siniscalco (1993), Finus, Altamirano-Cabrera, and Van Ierland (2005), and Bréchet, Gerard, and Tulkens (2011) for some examples]. This paper provides a straightforward method for evaluating the net benefits of correcting a global externality for individual countries or regions. We believe that it provides several benefits compared to the existing literature. Most important, the net benefit estimates are transparent and calculated in shares rather than levels. Further, these estimates can be used to calculate the side payments necessary to incentivize agreement to a globally efficient treaty as well as estimate the inefficiency of unilateral action to address climate change.

We also employ a novel measure of possible damages from future climate change. There are relatively few models of climate change damages at the national level, and even regional shares of damages tend to be extremely sensitive to parameter assumptions. For that reason, we use share of global GDP as a proxy for share of potential climate change damages. This could be an attractive measure if climate change damages are best understood as affecting the global economy, with each country's individual harm allocated on the basis of their participation in that economy. Share of global GDP would then better reflect how much each country has to lose. In addition, share of future global GDP is subject to much less uncertainty than the IAMs damage predictions.

The paper proceeds as follows. In Section 2 we develop a straightforward cost-benefit-based model of international environmental agreement formation and describe the simple estimate of net benefits. The next section describes the data taken from IAMs to estimate net benefits in international climate treaty negotiations. Section 4 applies the test to climate data and Section 5 concludes.

1 See Barrett (2005) for a summary of the literature.

2 Model

We model the costs and benefits of a straightforward negotiation to impose an efficient solution to a global environmental externality.[2] The model is stylized but provides a framework for identifying countries that are most likely to be better off under an efficient environmental agreement.[3] Countries are faced with a choice of joining a global treaty that obligates signatories to reduce emissions to the globally efficient level through means of an environmental tax or pollution permit scheme.[4] If every country ratifies, then the treaty goes into force, but if there is a single holdout, then the treaty lapses and no country reduces emissions. Potential signatories compare the benefits from global emissions reductions against the cost of domestic abatement, and if the benefits outweigh the costs, then they choose to sign the treaty. This structure eliminates the possibility of sub-global coalitions creating their own treaty and allows us to focus on globally efficient, cost minimizing agreements.[5] By estimating which countries clearly benefit from a globally efficient emission level vis-à-vis the status quo, we can identify those countries least likely to require a side-payment to achieve positive net benefits.

Country *i* faces a domestic marginal damage function of $MD_i(E)$, where E is the global emissions level. Country *i*'s marginal abatement cost function is $MAC_i(e_i)$, where e is the quantity of domestic emissions. Marginal damages are monotonically increasing in global emissions and marginal abatement costs are monotonically decreasing in domestic emissions. Country *i* will have positive net benefits from an agreement to reduce emissions from the unregulated level (e_i^{max} for domestic emissions and E_i^{max} for global emissions) to the globally efficient level (e_i^* domestically and E^* globally) without need of side-payments if:

$$\int_{E^*}^{E^{max}} MD_i(E) \geq \int_{e_i^*}^{e_i^{max}} MAC_i(e_i), \tag{1}$$

2 We choose to focus on an efficient solution to a global externality, but our model is sufficiently flexible to allow for any level of reduction in the externality.

3 We abstract from the treaty negotiation process and compliance issues to focus on identifying potential free riders. See Barrett (2005) and Barrett and Stavins (2003) for analysis of those issues.

4 We put off the form this treaty takes (emissions taxes or permit schemes) till the next section.

5 These sub-global climate coalitions and the associated free-rider problem is important in the context of international climate change negotiations. See Nagashima and Dellink (2008). This assumption allows us to detect potential free riders by identifying nations with positive net benefits under a climate agreement. If those countries attempt to hold out of an agreement, they will be recognized as free riders, presumably reducing their bargaining power. This assumption allows us to focus on the cost-benefit justification of international environmental agreements while putting aside the issues of external or internal stability that have been debated in the literature.

This equation can be arranged into a benefit-cost ratio:

$$\frac{D_i(E^{max})+AC_i(e_i^*)}{AC_i(e_i^{max})+D_i(E^*)}\geq 1, \qquad (2)$$

where D_i and AC_i are the damage and abatement cost functions of country *i*, respectively. If the inequality holds, country *i* is better off at the globally efficient level of emissions. The ratio behaves in an intuitive way: it is increasing in E^{max} and e_i^* and decreasing in e_i^{max} and E^*. It is also increasing in marginal damages and marginal abatement costs. This is simply a condition that the domestic benefit-cost ratio must be greater than one for a country to join the globally efficient treaty.

We assume a functional form on the marginal abatement cost and marginal damage functions to allow us to eliminate level variables and work with shares of damages and abatement costs. In particular, we assume that the damage and abatement cost functions are linear. These assumptions are conservative for identifying countries likely to be better off at the globally efficient emissions level, in the sense that type II errors are minimized. The more convex the MAC curve, the smaller the share of global damages that are necessary to compensate for domestic costs; concave MAC curves in the climate context are unlikely.[6] The consequences of non-linear damage curves for setting optimal carbon policy are discussed in Weitzman (2009) and Ackerman, Stanton, and Bueno (2010) among many others.

Under these assumptions, the costs of entry into an efficient environmental treaty is equal to the area under the marginal abatement cost function: a triangle with area equal to $\frac{1}{2}MAC_i(e_i^*)(e_i^{max}-e_i^*)$. The benefits of entry into the efficient environmental treaty are the domestic damages abated: $\frac{1}{2}(E^{max}-E^*)\{MD_i(E^{max})+MD_i(E^*)\}$.[7] Using this notation and the simplifying assumptions above, the model confirms that a country will be better off under an agreement to reduce emissions to the globally efficient level:

$$\frac{1}{2}(E^{max}-E^*)\{MD_i(E^{max})+MD_i(E^*)\}\geq\frac{1}{2}(e_i^{max}-e_i^*)MD_G(E^*),$$

6 Linear MAC curves are consistent with the metastudy conducted by Fischer (2006). Ellerman (1998) finds quadratic functions fit most regional MACs very well, but (with the exception of Brazil) the coefficients on the quadratic term are very small.

7 To see this simply, separate the area of benefits into two pieces, the rectangle below the optimal tax rate $(E^{max}-E^*)*MD_i(E^*)$ and the remaining area below the marginal damages curve and above the tax rate: $\left(\frac{1}{2}(E^{max}-E^*)\{MD_i(e^{max})-MD_i(E^*)\}\right)$. Sum these two areas and then combine terms.

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where $MD_G(E)=\Sigma_i MD_i(E)$ is the global marginal damages at emissions level E, which is simply the sum of each country's marginal damages at that emissions level. The globally efficient level of emissions E^* is the one that equates $MD_G(E)$ and $MAC_G(E)$.[8] This is simply a condition that the benefits (on the left hand side of the inequality) must exceed the costs of joining a globally efficient treaty.

The value of global emissions reductions is based on the domestic marginal damages, and the cost of domestic abatement is based on the global marginal damages. We will exploit this fact to move from dollar denominated measures of damages and abatement costs to shares of global totals. Rearranging these terms [assuming $MD_G(E^*)>0$], the conditions become that country *i* should enter the climate treaty if:

$$\frac{MD_i(E^{max})+MD_i(E^*)}{MD_G(E^*)} \geq \frac{e_i^{max}-e_i^*}{E^{max}-E^*}, \tag{3}$$

The term on the left hand side of the inequality is country *i*'s share of global damages times a constant based on the slope of the marginal damage function. The right hand side is the share of global emission reduction. The model can confirm that a country is better off under an efficient climate treaty, even with a constant damage function, if its share of global damages exceeds one-half its share of global emission reductions. As $\frac{\partial MD_i(E)}{\partial E}$ increases, the share of global damages required to fulfill the inequality decreases. This formulation eliminates the level of costs and benefits and focuses on shares, which may be easier to observe.

If every country's share of emissions reductions were exactly equal to its share of global benefits, the inequality will be satisfied for each country and a global treaty will come into force. The more inequitable the proportional distribution, the less likely it becomes that all countries will be better off under an agreement to reduce emissions to the globally efficient level. As the share of abatement becomes more concentrated in countries that will not receive significant benefits, the likelihood of getting agreement on an efficient price decreases.

While stylized, the model provides a basis for a simple test that can be taken to the data to identify countries that would be better off under an efficient climate treaty. This concept, based on the costs and benefits of domestic action, is distinct but related to the stability concept in the literature.[9] This approach allows

8 This equality holds comes from the definition of the efficient tax, which equates global marginal damages with global marginal costs.

9 D'Aspremont, Jacquemin, Gabszewicz, and Weymark (1983) first describe coalition stability in collusive price cartels, but the International Environmental Agreement literature has adopted

us to assess global and sub-global environmental treaties and determine which coalitions would be cost-benefit justified on a country-by-country basis. The heuristic described above is especially useful if we have more reliable data about the ratios $\frac{MD_i(E^*)}{MD_G(E^*)}$ and $\frac{e^{max}-e^*}{(E^{max}-E^*)}$ than about the values of the individual terms.

2.1 Permit allocation schemes

If the distribution of global emissions reductions and risks are relatively uneven, achieving agreement on an efficient emission price will be difficult. It is has been shown that, under these conditions, it may be possible to use emissions permits to redistribute abatement costs from high-cost to high-risk regions, which could induce all countries to join an efficient international treaty.[10] We now use the same framework to develop a permit allocation scheme that produces the globally efficient level of emissions while providing the wealth transfers necessary to incentivize countries whose costs exceed benefits to join a treaty.

We imagine a permit scheme in which a social planner distributes permits to polluting regions.[11] We follow the literature in assuming that utility is linear and that the social planner weights welfare equally across countries.[12] The number of permits is fixed at the efficient level of emissions E^*, but the distribution of those permits is flexible, to encourage agreement. If the social planner allocates permits to each country in proportion to its emissions at the globally efficient level, then the costs will mimic an efficient emission tax. By distributing fewer permits to regions that are clearly better off under the environmental agreement, and more permits to other regions, the planner can use the permits to produce an agreement.

Emissions permits in excess of a region's efficient share of global emissions can be traded at a price equal to global marginal damages. This represents a

this terminology as well. See Barrett (1994) for an early paper that analyzes coalition stability using a similar cost-benefit-style framework.

10 See Chander and Tulkens (1992) for an early example of how international transfers can help form cooperative agreements and Rotillon and Tazdat (1996) for an example of the form those transfers might take.

11 Of course, much of the difficulty in creating efficient international environmental policy is due to the lack of a social planner.

12 See Eyckmans and Tulkens (2003), Carraro, Eyckmans, and Finus (2006, p. 3), and Carraro and Siniscalco (1993). This ensures that utility is transferable across countries, meaning that transfers are equally weighted. It would be straightforward to extend this analysis to unequal weights using a social welfare matrix that weights transfers. This approach ignores numerous equity and political issues with these transfers that are beyond the scope of this paper.

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benefit to recipient countries. By including this benefit on the left hand side of the inequality from equation 3 and rearranging, we can solve for the required number of permits to ensure that each country is better off under an environmental treaty and that the global coalition is potentially cost-benefit justified for each member:

$$(E^{max}-E^*)\{MD_i(E^{max})+MD_i(E^*)\}+(P_i)MD_G(E^*)\geq MD_G(E^*)(e_i^{max}-e_i^*),$$

$$P_i=\frac{e_i^{max}-e_i^*}{(E^{max}-E^*)}-\frac{MD_i(E^{max})+MD_i(E^*)}{MD_G(E^*)}, \quad (4)$$

where P_i is the share of global permits in excess of a country's share of global emissions at the efficient level $\left(\frac{e_i^*}{E^*}\right)$. The number of permits is increasing in the quantity of abatement relative to the globally efficient emissions level and decreasing in the share of global damages.

2.2 Suboptimal taxes

The distribution of permit allocation described above relies on the transfer of pollution rights across countries. Certain types of transfers may be difficult for practical or political reasons. In the absence of a mechanism to facilitate transfers, the efficient outcome may only be achievable if net benefits are distributed relatively equally across all countries. We use the same model to examine two possible second-best strategies requiring less international cooperation and compare the results to the globally efficient outcome.

For the first second-best strategy, we assess the impact of an environmental tax set at less than the efficient level. Such a tax would decrease the costs and benefits of a global environmental treaty. The costs would decrease more quickly than the benefits,[13] implying that more nations would be likely to join the treaty as the tax rate declined. It is straightforward to use our framework to show the impact of uniform suboptimal environmental taxes:

$$\frac{MD_i(E^{max})+MD_i(E^{\alpha})}{MD_G(E^{\alpha})}\geq\alpha\frac{e_i^{max}-e_i^{\alpha}}{E^{max}-E^{\alpha}}, \quad (5)$$

13 The construction of the marginal damage and marginal benefits curves ensure that the last unit of pollution abated generates the least net benefits. This means any reduction in the environmental tax will increase the average net benefits of emissions reductions.

where E^{α} and e^{α} are the global and domestic level, respectively, of emissions under an emissions tax of $\alpha MD_i(E^*)$. This formulation presents a simple translation of the cost-benefit heuristic derived above for suboptimal environmental taxes. A country will join an environmental treaty that sets an environmental tax at 50% of the globally efficient level, for example, if its share of global benefits times the constant based on the slope of the marginal damage function exceeds *half* of its share of global abatement.

We can solve the same cost-benefit formulation for the threshold domestic emissions tax (as a function of the globally efficient level) that would incentivize a country to join a globally efficient treaty as another second-best approach. It is important to note that we are considering a globally efficient treaty, despite the fact that countries may each be abating either above or below the globally efficient level. This is the analog of the permit scheme described above. Some countries must tax at above the efficient level to compensate for the fact that other countries will tax at below the globally efficient level. This holds $E^{max}-E^*$, MD_G, and $e_i^{max}-e_i^*$ constant by assumption, allowing us to isolate the MD_is needed to produce an agreement. After solving for the MD_is, we can test the plausibility of that assumption.

Using the structure laid out above, we can easily determine the level at which countries become clearly better off under an environmental treaty. Rearranging equation 3 we have:

$$\rho_i \frac{MD_i(E^{max})+MD_i(E^*)}{MD_G(E^*)}=\frac{e_i^{max}-e_i^*}{(E^{max}-E^*)}, \tag{6}$$

$$\rho_i=\frac{e_i^{max}-e_i^*}{(E^{max}-E^*)}\frac{MD_G(E^*)}{MD_i(E^{max})+MD_i(E^*))}, \tag{7}$$

The ρ_i identified from these equations is the tax level (as a fraction of the globally efficient level) that brings a region to the potential coalition member category. We can then test the plausibility of the assumption that a globally efficient climate treaty is possible by evaluating individual nations' ρ_i to assess whether they will have an impact on the globally efficient emissions level.

3 International climate treaty negotiations

We now exploit the framework described above to analyze international climate treaty negotiations. Climate change is a clear example of a global environmental externality. Emissions from any country generate damages that are experienced worldwide. Negotiations to create limits on the emissions of greenhouse gases (GHGs) have consistently failed to achieve binding reductions and suffer from numerous holdouts. The actual abatement costs and damages associated with climate change are difficult to predict [see Tol (2005)], making the theoretical framework described above particularly useful. Several IAMs are available that predict global emissions reductions and damages associated with climate change at a regional level.[14]

Using this data, it is possible to test for the feasibility of a global climate change treaty using the heuristic described above. A number of papers assess the stability of climate change treaty coalitions using data from IAMs. Perhaps most similar to this paper, Bossetti et al. (2009) examine the stability of every possible coalition that could emerge from a 12-region IAM and tests for the ability of those coalitions to deliver environmentally significant emissions reductions. Bosetti, Carraro, De Cian, Massetti, and Tavoni (2012) explore how changing assumptions about the pure rate of time preference, social welfare aggregation, and climate change damage scenarios can affect the stability of the most environmentally effective coalitions.

This paper differs from the existing literature by using the insight from the simple model above to test for the domestic-level cost-benefit justification of a global climate change treaty using shares of global costs and benefits from a climate change treaty rather than their levels. The results, particularly for external stability, are straightforward and intuitive and potentially more accurate if the IAMs are better at predicting the distribution of climate change damages and abatement costs than their magnitudes.

3.1 Data

The ideal dataset to identify holdouts in climate change negotiations would include country-level estimates of the cost of reducing emissions and the potential damages from climate change. Specifically, such a dataset would estimate the present value of the discounted stream of future costs of implementing the optimal carbon price at the country level. These values would be merged with country-level estimates of the discounted stream of future damages from climate change. Unfortunately, due to the lack of necessary country-level data and the

14 See chapter 6 of Stern (2006) for descriptions of the issues and techniques used in Integrated Assessment Modeling and the current state of the IAM literature as well as Tol (2009) for a meta-analysis of recent models.

Table 1 WITCH region definitions.

Regions	Countries
USA	United States
WEURO	Western European EU Countries
EEURO	Eastern European EU Countries
KOSAU	South Korea, South Africa, and Australia
CAJAZ	Canada, Japan, and New Zealand
TE	Russia and Non-EU Eastern European Countries
MENA	Middle East and North Africa
SSA	Sub-Saharan Africa
SASIA	South Asia including India
CHINA	China including Taiwan
EASIA	South East Asia
LAM	Latin America, Mexico, and the Caribbean

The composition of global regions used in the WITCH model. See Bosetti et al. (2009) for a full description of the regional definitions.

inability to quantify the considerable uncertainties at micro levels, no such dataset exists.

While country-level data is typically unavailable, there are several estimates of costs and damages at the regional level from IAMs. To the extent that regions are carefully selected to be homogeneous, regional estimates should serve as a good proxy for the actions of individual countries. Estimates of the costs of reducing emissions at the regional level are available from the WITCH (World Induced Technical Change Hybrid) Policy Simulator produced by Fondazione Eni Enrico Mattei (FEEM). This project develops an integrated energy-economic-environment model to assess the impact of climate change policy on various economic variables. The model is described in Bosetti, De Cian, Sgobbi, and Tavoni (2009). Results are available for 12 regions designed to be reasonably homogenous in their response to emissions reductions. Specifically, Bosetti et al. (2009) argue that their regions are designed to "share similarities in terms of the structure of the economy, energy supply and demand and resource endowments."[15] The model can be used to predict regional GDP and GHG emissions from 2010 to 2100 under a variety of different emissions levels and policy scenarios. By comparing emissions under a "business as usual" scenario to forecasts under a variety of policy frameworks that cap atmospheric concentrations of GHGs, it is possible to calculate the share of global emissions reductions by region.

These regional abatement estimates are paired with regional damage estimates taken from several different sources. Nordhaus and Boyer (2000) provide

15 Detailed regional definitions for the WITCH model are detailed in Table 1.

regional damage functions for 13 global regions using the Regional Integrated Climate-Economy (RICE) model. The RICE model provides estimates of damages from climate change through a regional level damage function that translates changes in surface temperature to changes in consumption. This is accomplished by calculating the effects of temperature change on a sector-by-sector level and then summing for each region. Results are reported as a fraction of GDP loss under 2.5°C and 6°C warming by 2100. The regional definitions are slightly different than those used in the WITCH model, but they are sufficiently close to allow comparison for the regions that play an important role in international climate policy.

These efforts to quantify damages from climate change are incomplete. Many of the damages are currently unquantified and some damages may be difficult to predict *ex ante*. However, even if damages are systematically under- (or over-) estimated, this should not affect inference from existing data so long as all regions are equally likely to face unquantified and unpredictable damages. Of course, these probabilities cannot be determined. The theoretical specification is flexible enough to employ any estimated regional breakdown of climate change damages and abatement costs. As the science of climate modeling advances, the estimates can be plugged directly into this model.

4 Assessing a global climate change treaty

The theoretical framework laid out above requires comparing the portion of total world emissions reductions and damages avoided associated with an efficient global carbon price. Using a variety of data sources, we compare the fraction of world abatement and benefits at the regional level for which relatively precise estimates are available. The IAMs described above provide data that is consistent with the theoretical framework and can be used to identify regions that could see positive net benefits under a global climate treaty. We then consider several policy scenarios that may eliminate the unpriced externality while addressing the global nature of damages from GHG emissions.

We begin by estimating the fraction of emissions reductions borne by different regions using data from the WITCH model. The model is used to estimate GHG emissions under a variety of scenarios: business as usual, an emissions reduction sufficient to reduce atmospheric concentration to 640 parts per million (which is associated with warming of around 24°C), and an emissions reduction sufficient to reduce atmospheric concentration to 535 ppm (associated with warming of 2.6°C). The 535 ppm emissions scenario can be paired with an implementation policy option to analyze how proposed cost containment strategies affect costs. The least expensive implementation scenario employs “all technologies and policies” to minimize costs, including emissions trading, offsets, and renewable technologies. The most expensive policy option is labeled “no backstop technology,” which assumes no technological improvement in either the energy or non-energy sector over the remainder of the century.

The WITCH model projects emissions every 5 years from 2010 to 2100 in each scenario. We compile those projections and subtract the difference between emissions under a business-as-usual scenario and under each policy option. Using these projected emissions reductions, it is straightforward to estimate the share of global reductions expected in each region. We then find the scenario with the maximum and minimum emissions reduction shares for each region. This range of possible reduction shares is reported in Table 2. Though there is a great deal of heterogeneity across regions, the different scenarios provide remarkably similar emissions reductions predictions. China will face the highest level of emissions reductions over the remainder of the century at around 25%, while Eastern European countries will only provide 1.5% of global emissions reductions.

Due to the long halflife of carbon and the slow movement of the global climate cycle, even sharp reductions in emissions will not guarantee full avoidance of

Table 2 Share of global emissions reductions by region.

Region	Min	Max
USA	16.1	17.1
WEURO	5.9	6.7
EEURO	1.5	1.7
KOSAU	2.7	3.0
CAJAZ	3.0	3.2
TE	6.1	6.6
MENA	4.4	6.1
SSA	4.0	4.5
SASIA	11.9	13.8
CHINA	24.4	26.4
EASIA	5.1	6.2
LAM	8.1	10.5

The range of emissions reductions shares from eleven different parameterizations of the WITCH model. Units for each column are regional share of global climate emissions reductions. The variation across different versions of the model is considerably less than the variation across regions.

these damages.[16] When determining whether to enter a treaty to reduce emissions, governments are presumably comparing the present value of abatement costs to the marginal reductions in damages that abatement will generate. The IAMs we use do not provide mappings from current emissions reductions into damages averted, but they do provide estimates of damages (typically measured as a fraction of output) associated with various temperature increases. In the absence of data on the proportional benefit of marginal decreases in GHG emission, we use the proportion of total exposure as a proxy. Using temperature-based measures of total exposure may also be the appropriate measure for modeling the treaty formation process if the decisions of negotiators are based on these measures of damages, which are the best currently available.

We use the RICE [described in Nordhaus and Boyer (2000)] for regional climate change damages.[17] Additionally, we use projected future GDP as a proxy for share of global damages. Climate change is likely to generate damages that spill across international boundaries, such as generating frictions in international trade markets or causing unrest that requires the expenditure of national defense resources. These cost spillovers make regional attribution of damage difficult. For that reason, regional GDP provides a useful alternative measure of exposure to climate change damages. In Fawcett (2009), the EPA suggests shares of global GDP to approximate the fraction of global climate change damages to which the United States might be exposed. To our knowledge, no other paper in this literature has used this approach when assessing the feasibility of a global climate change treaty.

Having compiled estimates of the costs of abatement and the possible damages from climate change at the regional level, we can determine which countries are least likely to be worse off under a global climate treaty. We use the midpoint of the range of possible emissions reduction shares from the WITCH model.[18] We then calculate each region's share of global damages as estimated under the RICE and WITCH models. Because both models' damages are reported as fractions of GDP in future years, it is necessary to translate these estimates into a common unit of measure before calculating each region's fraction of world costs. To do this, we use GDP projections from the WITCH model business-as-usual scenario. One additional difficulty remains: the two different models used

16 Climate damages are a function of the stock of pollution, while emissions are directly related to abatement costs. We use the terms *abatement* and *emissions avoided* interchangeably.

17 It is important to note that these estimates are sensitive to the IAMs used to calculate marginal benefits and marginal damages. If these models are incorrect about the distribution of future damages from climate change, that error will be propagated in our estimates.

18 Because of the relatively consistent emissions reductions estimates, the results are not sensitive to using other plausible measures.

to calculate abatement costs and damages define their regions slightly differently. Some large economies are defined consistently across the models, but smaller regions are inconsistent. To compare the fraction of world costs and damages, we choose to combine regions from the two damage estimates to match the WITCH regions that include the most aggregated regional definitions.

By multiplying the estimated climate change damages from RICE and GDP shares by the appropriate WITCH GDP forecast, it is possible to report damages in billions of 2005 US $ (the unit of measure used by WITCH). By summing the dollar value of damages, we can estimate the total world damages from climate change and then find each region's fraction of those damages. This generates an estimate of damages from climate change consistent with the stylized model at the regional level. Paired with cost estimates from the WITCH model, we can compare the fraction of world damages to the fraction of world costs and apply the heuristic to identify regions that are least likely to have an incentive to avoid imposition of a globally efficient carbon price. This analysis is predicated on a globally efficient emissions treaty with a commitment period of 2015–2100. Differential growth rates in GDP, emissions, and damages across regions imply that treaties with different commitment periods would require a separate analysis, but this method will effectively estimate net benefits across any commitment period.

To simplify notation and focus on our climate change case study, we take advantage of the concept of the "social cost of carbon," which represents the marginal damages generated by a ton of carbon emissions at a given global emissions level: $SCC_G=MD_G(E)$. A flat damage function implies that SCC is the same for all values of E. The global social cost of carbon can be considered the sum of the domestic social costs of carbon for every country in the world. We denote the global social cost of carbon as SCC_G and domestic social cost of carbon as SCC_i. Setting the efficient global tax at SCC_G would generate $\sum_i MAC_i(e_i^*)=\sum_i MD_i(e_i^*)$. We further assume that the $MD_i(E)$ is a constant for all countries. This is a conservative assumption that further reduces the risk of false positives for a positive domestic net benefit country.[19] These estimates represent a lower bound on the level of climate treaty participation that could be expected at the globally efficient price. To the extent that marginal damages are increasing, regions on the margin become more likely to join a treaty. Using this new notation and our more conservative assumption on the shape of the MD curve, the condition for a country to join an efficient global climate change treaty becomes:

19 The assumption is conservative in the sense that constant marginal damages minimizes the total benefits of joining a climate change treaty to lower emissions to a given level. Any country that would agree to a climate change treaty under constant marginal damages would agree if its marginal damage function was increasing.

$$\frac{SCC_i}{SCC_G} > \frac{1}{2}\frac{e_i^{max} - e_i^*}{(E^{max} - E^*)} \tag{8}$$

If region *i*'s share of global benefits exceeds half its share of global costs, then they are better off under an efficient international agreement. If every region satisfies this inequality, then net benefits are positive everywhere and the global treaty will come into force. As the slope of the marginal damage curve increases, this one-half weight falls, and the likelihood of a region being better off under a treaty and an agreement being cost-benefit justified increases.

Table 3 provides three estimates of $\frac{SCC_i}{SCC_G}$ based on different sources of damage estimates in columns 1–3 and $\frac{e_i^{max} - e_i^*}{(E^{max} - E^*)}$ in column 4. Comparing the damage estimates to one-half of the abatement estimates allows us to identify clear winner (CW) regions under these conservative assumptions. Focusing on individual regions, Western Europe and South Asia appear most exposed to climate change damages, while China and the United States face the largest abatement requirements. Several regions are clearly better off under a globally efficient climate change treaty no matter which damage specification is used (Western Europe, South Asia, Latin America); other regions are sensitive to the source of the damage estimates. If damages are likely to spill over national borders, then the GDP share may be the best proxy for true damages. In that case, joining a climate treaty would be cost-benefit justified for both China and the United States.[20] Table 4 provides a summary of whether a region would join a global climate treaty based on a given damage estimate.

If each region satisfies the inequality above, then a global climate change treaty would be cost-benefit justified for all countries. The results suggest that under the RICE damage estimates a global coalition would not be feasible, as several regions, including the largest emitters, would be holdouts. The damage estimates based on GDP shares suggest that a global treaty would be cost-benefit justified for all countries. Each global region satisfies the inequality, but Russia

20 It should be noted that these estimates are based on the conservative assumptions laid out above. As the slope of the marginal damage curve increases, there are thresholds over which both countries become better off under a globally efficient climate treaty. If the damages curve for China is steep enough so that $MD_i(E^{max})$ is 10.5 times greater than $MD(E^*)$, then China would be better off under a global climate change treaty even if its share of global damages is only 2.2%. For the US, the comparable figure is 3.9. If the unregulated level of damages exceeds the domestically efficient level by more than 3.9 times, then the US would be better off under a global climate treaty using even the smallest share of global benefits as the basis for our estimate.

Table 3 Regional share of damages and abatement.

Column	RICE		WITCH	
	2.5°C	6°C	GDP Share	Abatement
	1	2	3	4
USA	4.3	7.3	17.3	16.6
WEURO	20.8	24.4	13.3	6.3
EEURO	0.6	0.7	1.6	1.6
KOSAU	2.2	2.2	2.2	2.8
CAJAZ	−1	3	4.5	3.1
TE	−1.1	2.9	3.1	6.3
MENA	6.1	2.5	5.7	5.2
SSA	9.6	1.7	4.4	4.3
SASIA	38	30.3	13.9	12.9
CHINA	2.2	8.9	17.8	25.4
EASIA	6.1	4.4	4.1	5.6
LAM	12.1	11.7	12.1	9.3

Columns 1 and 2 display each region's share of global climate change damages as estimated by the RICE model. Column 3 lists each region's share of global GDP in 2100 as approximated by the WITCH model, which may be considered a proxy for exposure to future damages. Column 4 lists the midpoint of the range of each region's share of abatement as predicted by the WITCH model.

Table 4 Regional share of damages and abatement.

Column	RICE		WITCH
	2.5°C	6°C	GDP Share
	1	2	3
USA	N	N	Y
WEURO	Y	Y	Y
EEURO	N	N	Y
KOSAU	Y	Y	Y
CAJAZ	N	Y	Y
TE	N	N	N
MENA	Y	N	Y
SSA	Y	N	Y
SASIA	Y	Y	Y
CHINA	N	N	Y
EASIA	Y	Y	Y
LAM	Y	Y	Y

Columns 1–3 display whether a region would join a globally efficient climate treaty using the share of global damage estimate from the source listed in the column header. Y indicates the region would join the treaty. N indicates that the region would require a side-payment to join.

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and Eastern Europe have close to zero net benefits under a globally efficient treaty.

4.1 Permit allocations

High-risk countries can choose to receive less than their proportional share of permits and provide permits to countries that face a high fraction of the required total emissions reductions. A careful distribution of permits will provide incentives for all countries to join an efficient international climate treaty. Numerous papers have attempted to solve for permit schemes that produce stable climate change coalitions,[21] but we take advantage of the heuristic described above, which may be more robust to measurement error since it operates on shares rather than levels.

By construction of the model, there must be enough regions that experience net gains from emissions reductions to provide permits to those that do not, ensuring that under this framework a global coalition is feasible. It is still useful to trace the flow of permits and assess the political feasibility and equity impacts of these coalitions. Simplifying equation 4 to account for our linear damage function produces the following equation:

$$P_i = \frac{1}{2}\frac{e_i^{max} - e_i^{*}}{E^{max} - E^{*}} - \frac{SCC_i}{SCC_G}, \tag{9}$$

where P_i is the share of global permits in excess of a country's share of global emissions at the efficient level $\left(\frac{e^{*}}{E^{*}}\right)$. The number of permits is simply the gap between the share of damages and half the share of abatement. Using the data described above, we are able to determine the number of permits relative to a region's share of emissions required to produce a global treaty pricing emissions at the efficient carbon price.

Table 5 describes the minimum number of permits required to induce regions to join a global treaty, or the number of permits that regions would be willing to provide to encourage other regions to sign on. The entries in the table represent the number of permits above (or below) their share of global emissions. The units are indexed such that the globally efficient level of emissions is 100. For example, using the RICE model 2.5°C damage estimates, China would need to receive an excess allocation of permits equal to 10.5% of global emissions reductions and

21 See Eyckmans and Tulkens (2003), Carraro et al. (2006), and Germain, Toint, Tulkens, and de Zeeuw (2003), among many others.

Table 5 Permit flows across regions.

	RICE		WITCH
	2.5°C	6°C	GDP Share
USA	4.0	1.0	−9.0
WEURO	−17.7	−21.3	−10.1
EEURO	0.2	0.1	−0.8
KOSAU	−0.8	−0.8	−0.8
CAJAZ	2.6	−1.5	−2.9
TE	4.3	0.3	0.1
MENA	−3.5	0.1	−3.1
SSA	−7.5	0.5	−2.3
SASIA	−31.6	−23.9	−7.4
CHINA	10.5	3.8	−5.1
EASIA	−3.3	−1.6	−1.3
LAM	−7.5	−7.1	−7.4

The share of additional permits required to incentivize agreement to a globally efficient carbon price measure relative to the globally efficient emissions level (E^*). Units are indexed such that the globally efficient level of emissions is 100. Negative numbers represent permit outflows.

Western Europe would be willing to accept an allocation of permits 17.7% of global emissions less than its share. The United States would need to receive permits totalling 1%–4% of total emissions reductions under the damage estimates produced by the RICE model, but it would provide permits equal to 9% of total emissions reductions based on the GDP proxy for damage.

This permit scheme represents a straightforward method to encourage all regions to join a global climate agreement. While such an agreement might be technically feasible, it might face domestic political backlash. It may be difficult to convince Latin Americans to forgo permits in exchange for the United States' agreement, or for South Asia to send permits to China. However, because Western Europe is willing to give up a relatively large number of permits, it may be possible to provide adequate compensation from its pool of permits. It appears that under these damage scenarios, globally efficient climate treaties are possible if Western Europe is willing to provide significant transfers to the United States and China. A global climate treaty would be domestically cost-benefit justified for all countries without any transfers if global GDP shares are used as a measure of damages. The negative numbers indicate each region would be willing to give away permits in this scenario, although none should have to do so.

4.2 Suboptimal carbon prices

Using the heuristic and data described above, there are several regions that we cannot confirm would be better off under a globally efficient carbon price without permit transfers. Recall that equation 5 allows us to find a suboptimal carbon price at which countries that do *not* experience positive net benefits would be willing to join a self-enforcing treaty. Under our simplifying assumptions, a suboptimal carbon tax reduces the "break even" ratio of share of benefits and share of costs from one-half to something less. Specifically, a country will be better off joining a climate treaty imposing a carbon tax at α of the globally efficient level if its share of global damages avoided is more than $\frac{1}{2}\alpha$ its share of global abatement.

For example, if an international climate treaty were proposed that set a carbon price at half the global social cost of carbon for a single country, then that country would be better off joining a global climate treaty if its share of global benefits exceeded $\frac{1}{4}$ its their share of global emissions reductions. Other nations would have to pay a higher tax rate so the emissions-weighted average tax was at the globally efficient level.

We now turn to estimating what level of domestic carbon tax these countries would accept to join a treaty that reduces emissions to the globally efficient level. This scenario imagines a global treaty with differential carbon taxes based on each region's share of global damages and abatement. The emissions-weighted average tax would be equal to the global marginal damages producing an efficient emissions level. Recall that SCC_G is the global marginal damages of a ton of carbon emissions, or in other words, the globally efficient carbon price. Using our estimates of regional abatement costs and damages and equation 7, we can find the ρ_i that solves:

$$\rho_i = \frac{1}{2}\frac{e_i^{max} - e_i^*}{(E^{max} - E^*)}\frac{SCC_G}{SCC_i}, \tag{10}$$

for each region. This ρ_i represents the threshold fraction of the global social cost of carbon that exactly equates the regional costs and benefits of joining a global climate treaty, which we refer to as the "break-even" tax rate. Table 6 lists the threshold fraction of the globally efficient carbon price that would leave each region on the margin of joining a global treaty for each of our three damage share estimates. For example, using the RICE model's damage estimates, the United States should be willing to join an agreement to reduce total emissions to the efficient level if it were allowed to price carbon at 52% of the globally efficient level.

A globally efficient climate treaty is possible if the emissions-weighted average of each region's ρ is equal to or larger than the globally efficient tax level. Recall

Table 6 "Break-even" carbon tax rates for various damage estimates.

	RICE		WITCH GDP
	2.5°C	6°C	GDP Share
USA	51.9	88.0	209.2
WEURO	661.4	775.9	421.7
EEURO	74.5	86.9	197.1
KOSAU	155.1	155.1	157.8
CAJAZ	−64.4	193.1	287.3
TE	−34.7	91.4	96.7
MENA	234.1	95.9	217.7
SSA	451.7	80.0	208.1
SASIA	590.3	470.7	215.6
CHINA	17.3	70.1	140.4
EASIA	217.2	156.7	147.5
LAM	259.7	251.1	259.5

The "break-even" carbon tax rate measures the maximum percentage of the globally efficient price on carbon that regions would be willing to impose domestically as part of a globally efficient climate treaty.

that this specification assumes that $E^{max}-E^{*}$, SSC_G and $e_i^{max}-e_i^{*}$ do not change despite country *i* instituting a carbon price different from the global optimum. By construction, the emissions-weighted average of ρ is <1, suggesting that it would be possible to produce a globally efficient level of emissions using differential taxes, but this is not sufficient to ensure that these assumptions are reasonable.

We can evaluate this assumption by looking at the individual ρs and determining whether the globally efficient level of emissions is likely to change. For example, using the RICE model 2.5 °C damage estimates, Western Europe would be willing to pay a carbon tax over six times the globally efficient level, but China would only pay a tax at 17% of the efficient level. This implies that abatement costs are likely to be significantly higher in Western Europe than in China, thus increasing the globally efficient level of emissions and violating our assumption.

Allowing individual countries to set their own carbon tax is unlikely to generate anything approaching a globally efficient climate treaty. If an agreement including differential tax rates allowed for emissions offsets for abatement undertaken in low-cost regions, Western Europe could pay for abatement in China; however, this arrangement is very similar to the wealth transfer through permit allocation scheme described above. Without such a scheme, differential carbon tax rates across countries based on shares of global abatement and damages are not particularly useful.

5 Conclusion

This paper develops a stylized model of international agreement on transboundary externalities. Under plausible assumptions, the results provide a simple way to determine which countries would be extremely unlikely to face incentives to oppose a globally efficient price on the externality, if the alternative is the status quo. By comparing the proportion of total abatement to the proportion of total risk, it is possible to apply a simple heuristic to categorize some countries as clear winners. If the shares of global abatement and risk are relatively evenly distributed, an international agreement to price the externality is straightforward to implement. If the distribution of either emissions reduction or damages is uneven, then it is possible to calculate a distribution of pollution permits that eliminates the incentive for any countries to oppose a globally efficient agreement to price the externality.

The data suggest that five of twelve global regions (accounting for 37% of total emissions reductions) are all clearly better off under a global climate treaty. We then determine how many permits each region would need to be allocated to encourage it to sign on to a globally efficient carbon price. China would have to receive an allocation of permits of between 2% and 11% of world emissions more than its share of global emissions. If countries believe that share of global GDP is a good proxy for potential damages from climate change, then a global climate treaty appears cost-benefit justified for all countries. However, if countries believe climate change costs are unlikely to spill over borders and their domestic damages are the appropriate measure, then transfers will be necessary to produce an efficient global treaty. Allowing differential emissions taxes across global regions based on shares of global abatement and damages would be unlikely to generate an efficient emissions level. Note that these estimates rely on constant marginal damages. If marginal damages are increasing, then we have understated the benefits of joining a climate treaty. For that reason, our estimates should serve as a lower bound for climate treaty participation.

We believe that this approach provides a more straightforward way to estimate the domestic costs and benefits of a globally efficient carbon price than the existing literature, but it is not without its drawbacks. We rely on an assumption of constant marginal damages in the application, which may significantly understate the benefits of a globally efficient carbon price. For that reason, these estimates should be considered a lower bound on regional net benefits and an upper bound on permit flows. We also assume linear marginal cost curves, which is empirically justified for carbon emissions but may not be for other global pollutants. Perhaps most important, this approach requires an understanding of the marginal damage and marginal cost functions at the country level. If the marginal damage or marginal abatement curves shift,[22] then the net benefits of internalizing a global externality will have to be recalculated. Unfortunately, most existing estimates of this type are sensitive to the same assumption; less restrictive assumptions may prove more appropriate.

This paper has assumed a status quo right for countries to allow uncontrolled emission of pollutants with negative global effects. This need not be the case. If the international community were to operate under a "polluter pays" principle, the United States and China would face huge liabilities for their emissions, while regions exposed to risk would be compensated for those damages. Under these conditions, countries would face entirely different incentives to reduce pollution. This paper also made restrictive assumptions on the shape of the marginal damage and abatement curves in each region. As more data becomes available on the damages associated with climate change and the relative costs of abatement, these assumptions might be relaxed.

International negotiations over international environmental agreements are based on much more than strict cost-benefit analysis. There are issues of fairness, equity, and political concerns. This work does not address those issues, but it may still be useful in understanding international negotiations by allowing participants to understand the cost-benefit related issues that each region faces. This may allow negotiators to separate countries that are truly worse off in a global climate coalition from those that are merely claiming to be worse off in an effort to free ride.

Appendix

Constant Damage Function

This appendix explores the impact of unilateral emissions reductions on the decision to enter a global climate treaty. Define a new emissions level $\hat{E}$ that is the global level of emissions under unilateral action. If each country reduces emissions to the domestically efficient level by emitting where the $MD_i=MAC_i$, ignoring any spillover effects, then they will emit $\hat{e}$. In this case, a country would never abate past its domestically efficient emissions level. Low-cost abatement

22 For example, marginal damage curves could shift due to better scientific understanding of the damages of climate change or regime shifts due to increasing stock of pollutants. Similarly marginal abatement costs could shift due to technological breakthroughs in carbon capture and sequestration or geoengineering.

opportunities in low-damage countries would not be employed, while relatively higher cost abatement in high-damage countries would be used.

Assume (for the time being) that marginal damages are constant. Define a set of useful marginal damage levels:

	Domestic damages	Global damages
Unilateral Action	$MD_i(\hat{E})$	$MD_G(\hat{E})$
Global Agreement	$MD_i(E^*)$	$MD_G(E^*)$
No Regulation	$MD_i(E^M)$	$MD_G(E^M)$

The pollution tax rate in country *i* is simply the domestically efficient environmental tax, which (under the constant damage function assumption) is the same under unilateral or global action, $MD_i(\hat{E}) = MD_i(E^*) = MD_i(E^M)$. Similarly, $MD_G(\hat{E}) = MD_G(E^*) = MD_G(E^M)$. The benefits and costs of each type of emissions reductions are:

Benefits under a global agreement	Costs under a global agreement
$MD_i(E^*)(E^M - E^*)$	$\frac{1}{2}MD_G(E^*)(e^m - e^*)$

Benefits under unilateral action	Costs under unilateral action
$MD_i(E^*)(E^M - \hat{E})$	$\frac{1}{2}MD_G(E^*)(e^m - \hat{e})$

The net benefits of a global climate treaty for country *i* is: $MD_i(E^*)(E^M - E^*) - \frac{1}{2}MD_G(E^*)(e^m - e^*)$. The net benefits of unilateral action to reduce climate change for country *i* is: $MD_i(E^*)(E^M - \hat{E}) - \frac{1}{2}MD_G(E^*)(e^m - \hat{e})$. If the net benefits in country *i* of global action exceed the net benefits of unilateral action, then country *i* will join a global climate treaty. Comparing those net benefits we find:

$$MD_i(E^*)(E^M - E^*) - \frac{1}{2}MD_G(E^*)(e^m - e^*) \geq MD_i(E^*)(E^M - \hat{E}) - \frac{1}{2}MD_G(E^*)(e^m - \hat{e})$$

$$MD_i(E^*)(E^M - E^*) - MD_i(E^*)(E^M - \hat{E}) \geq \frac{1}{2}MD_G(E^*)(e^m - e^*) - \frac{1}{2}MD_G(E^*)(e^m - \hat{e})$$

$$MD_i(E^*)[\hat{E} - E^*] \geq \frac{1}{2}MD_G(E^*)[\hat{e} - e^*]$$

$$\frac{MD_i(E^*)}{MD_G(E^*)} \geq \frac{1}{2}\frac{\hat{e} - e^*}{\hat{E} - E^*}$$

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A country will join a global agreement if its share of global damages exceeds half of its share of emissions reductions from the unilateral to the globally efficient level. This is a simple extension of the previous model, where emissions reductions are measured relative to the unilateral-action emissions level $(\hat{e})$ rather than the unregulated emissions level (e^M).

Ignoring the option for unilateral action will be a conservative assumption (in the sense that it will avoid the possibility of falsely identifying treaty signatories) if a region is more likely to agree to a global treaty when considering opportunity costs than when ignoring them. We can estimate when this will happen by comparing the condition for acceptance with and without opportunity cost. If

$$\frac{(e^m-e^*)}{(E^m-E^*)}\geq\frac{\hat{e}-e^*}{\hat{E}-E^*}$$

holds, then ignoring unilateral action is a conservative assumption.

Increasing Damage Function

Using the same notation, consider the case of a linear but monotonically increasing damage function. For this case, we redefine the benefits of entering a global treaty as the benefits of moving the unilaterally efficient emissions level $(\hat{e})$. Rearrange equation to describe the benefits of moving from the unilateral to globally efficient level of emissions as:

$$\frac{MD_i(\hat{E})+MD_i(E^*)}{MD_G(E^*)}\geq\frac{\hat{e}-e^*}{(\hat{E}-E^*)}$$

This assumption will be conservative if

$$\frac{e^M-e^*}{(E^M-E^*)}-\frac{MD_i(E^M)}{MD_G(E^*)}\geq\frac{\hat{e}-e^*}{(\hat{E}-E^*)}-\frac{MD_i(\hat{E})}{MD_G(E^*)}$$
$$\frac{e^M-e^*}{(E^M-E^*)}-\frac{\hat{e}-e^*}{(\hat{E}-E^*)}\geq\frac{MD_i(E^M)-MD_i(\hat{E})}{MD_G(E^*)}$$

The left hand side of the inequality is positive if a country's share of global abatement moving from no emissions reduction to the globally efficient level is greater than its share of abatement moving from the unilateral action outcome to the globally efficient level. The right hand side is the reduction in a country's marginal damage between E^M and $\hat{E}$ as a fraction of the global damages at the efficient level.

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