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Abstract

Unilateral carbon policies are inefficient due to the fact that they generally involve emission reductions in countries with high marginal abatement costs and because they are subject to carbon leakage. In this paper, we ask whether the use of carbon tariffs—tariffs on the carbon embodied in imported goods—might lower the cost of achieving a given reduction in world emissions. Specifically, we explore the role tariffs might play as an inducement to unregulated countries adopting emission controls of their own. We use an applied general equilibrium model to generate the payoffs of a policy game. In the game, a coalition of countries regulates its own emissions and chooses whether or not to employ carbon tariffs against unregulated countries. Unregulated countries may respond by adopting emission regulations of their own, retaliating against the carbon tariffs by engaging in a trade war, or by pursuing no policy at all. In the unique Nash equilibrium produced by this game, the use of carbon tariffs by coalition countries is credible. China and Russia respond by adopting binding abatement targets to avoid being subjected to them. Other unregulated countries retaliate. Cooperation by China and Russia lowers the global welfare cost of achieving a 10% reduction in global emissions by half relative to the case where coalition countries undertake all of this abatement on their own.

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1 Introduction

A central preoccupation of the international climate-change debate is the question of when developing nations should accept binding targets on their carbon emissions. Developing countries argue that, in the near term, it is unfair to ask them to cut back on their emissions without compensation for the effect it would have on their prospects for economic growth. At the same time, the unilateral carbon policies currently being pursued (or contemplated) by developed countries are likely to be highly inefficient due to the fact that these countries have relatively high abatement costs. Unilateral policies are also subject to carbon leakage which reduces the global cost effectiveness of subglobal action even further (Hoel 1991, Felder and Rutherford 1993).

In theory, a global emissions cap-and-trade system could deliver on the demands of developing countries and control world emissions in a cost-effective way. However, there remains considerable skepticism that such a system is practical. The monitoring and enforcement challenges as well as the large and explicit transfers of wealth that global emissions trade would impart to countries with limited institutional capacities make finding the political will to implement such a scheme difficult (McKibbin and Wilcoxen 1997).

Against this background, several policy analysts have noted that trade policies could serve as a means for regulating carbon emissions in countries that have no domestic emission regulations of their own. The reasoning behind is that developed countries are net importers of embodied carbon emissions from their developing world trade partners. Trade policies could work directly by stifling demand for carbon-intensive goods produced in developing countries. They could also work indirectly as an environmentally-sanctioned punishment that speeds the adoption of emission controls in those countries.

One popular proposal for climate-motivated trade restrictions involves the use of embodied carbon tariffs, i.e. tariffs levied on the direct and indirect carbon emissions embodied in imported goods. Carbon tariffs have support as a form of direct regulation from the theory of second-best environmental taxation (Markusen 1975, Hoel 1996). If governments cannot regulate foreign emissions at the source, tariffs may be justified from a global efficiency perspective. On the other hand, there are substantial practical and legal costs that would inevitably come with their use (Brewer 2008, Pauwelyn 2007, Howse and Eliason 2008, Charnowitz, Hufbauer and Kim 2009). Furthermore, quantitative evidence from applied general equilibrium (CGE) analyses suggests that the use of embodied carbon tariffs is unlikely to result in substantial reductions in the global cost of achieving emission reductions through unilateral action. The main effect of carbon tariffs is to shift the burden of policy to the countries subjected to them (Böhringer, Carbone and Rutherford 2011, Mattoo, Subramanian, Mensbrugghe and He 2009, Babiker and Rutherford 2005, Böhringer and Rutherford 2002).

In this paper, we explore the indirect role carbon tariffs might play as an environmental sanction. Their burden-shifting effect means that they have the potential to confer substantial trade gains to the countries that use them, making them politically attractive there. They also have the potential to inflict damage on the countries subjected to them. Thus unregulated countries may prefer to adopt emission controls of their own than suffer the effects of the tariffs, a strategic response that could significantly lower the global cost of climate policy. On the other hand, these countries may prefer to adopt countervailing tariffs of their own rather than suffer the cost of emissions regulation, a response that could significantly increase costs.[1]

In this paper we ask: which of these regimes is likely to arise from the self-interested policy choices of nations and what does it mean for the prospect of designing effective international responses to climate change? To answer these questions we use an applied general equilibrium model of the world economy and carbon emissions to generate the payoffs of a policy game. In the game, a coalition of Annex-I countries (those countries that agreed to take on abatement responsibilities under the Kyoto Protocol) is commited to reducing global emissions to 10% below business-as-usual levels, a target consistent with their commitments under the Kyoto Protocol. To achieve this, the coalition regulates its own emissions domestically using a uniform carbon tax. In addition, it chooses whether or not to deploy carbon tariffs against non-coalition countries with unregulated emissions. Non-coalition countries may respond by adopting emission regulations of their own, retaliating against the carbon tariffs by engaging in a trade war, or by taking no action and simply leaving their emissions unregulated. Equilibria of the game are policy regimes in which no non-coalition country wishes to change its policy given the policies of others and in which the coalition chooses whether or not to use carbon tariffs to maximize its payoff anticipating the best responses of non-coalition countries.

In the unique Nash equilibrium prediction produced by this game, the use of carbon tariffs by coalition countries is credible. China and Russia — two major emitters outside the Annex I abatement coalition — respond by adopting binding abatement targets to avoid being subjected to carbon tariffs. All other non-coalition countries retaliate. Cooperation by China and Russia lowers the global welfare cost of achieving a 10% reduction in global emissions by half relative to the case where coalition countries undertake all of this abatement on their own.

China and Russia are motivated to cooperate for two main reasons. First, they avoid the punishment of carbon tariffs by doing so. Second, these countries are quite dependent on the performance of coalition economies, as a destination market for their exports and as the origin of imports. When China and Russia take on abatement, less is required of coalition countries to meet the assumed 10% reduction target. In addition, the overall efficiency of the global economy improves when these countries take on more of the global abatement burden because they are the source of low-cost abatement opportunities. Thus, the global pattern of abatement effort moves closer to a first-best allocation. Both of these effects benefit China and Russia.

[1]Many policymakers have expressed concern that the specter of the tariffs could disrupt on-going international climate policy negotiations (Houser, Bradley and Childs 2008) or trade relations (ICTSD 2008).

The rest of the paper proceeds as follows. Section 2 briefly describes the structure of the CGE model and the database we use to generate the payoffs for our policy game. Section 3 describes the structure of the policy game we study and the details of the specific policy options countries face within the game structure. Section 4 describes the results of our main policy experiments. Section 5 covers the results of sensitivity analysis with respect to some key assumptions in the CGE model and the policy game. Section 6 concludes with a discussion of the policy significance of our results and possible extensions.

2 Model and Data

In our analysis, we adapt a generic multi-region, multi-sector CGE model of global trade and energy use established for the analysis of greenhouse gas emission control strategies by Böhringer and Rutherford (2010).[2] The model features a representative agent in each region that receives income from three primary factors: labor, capital, and fossil-fuel resources. Labor and capital are intersectorally mobile within a region but immobile between regions. Fossil-fuel resources are specific to fossil fuel production sectors in each region. Production of commodities, other than primary fossil fuels is captured by three-level constant elasticity of substitution (CES) cost functions describing the price-dependent use of capital, labor, energy and materials. At the top level, a CES composite of intermediate material demands trades off with an aggregate of energy, capital, and labor subject to a constant elasticity of substitution. At the second level, a CES function describes the substitution possibilities between intermediate demand for the energy aggregate and a value-added composite of labor and capital. At the third level, capital and labor substitution possibilities within the value-added composite are captured by a CES function whereas different energy inputs (coal, gas, oil, and electricity) enter the energy composite subject to a constant elasticity of substitution. In the production of fossil fuels, all inputs, except for the sector-specific fossil fuel resource, are aggregated in fixed proportions. This aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution.

Final consumption demand in each region is determined by the representative agent who maximizes welfare subject to a budget constraint with fixed investment (i.e., a given demand for savings) and exogenous government provision of public goods and services. Total income of the representative household consists of net factor income and tax revenues. Consumption demand of the representative agent is given as a CES composite that combines consumption of composite energy and an aggregate of other (non-energy) consumption goods. Substitution patterns within the energy bundle as well as within the non-energy composite are reflected by means of CES functions.

[2] A detailed algebraic model summary as well as schematic representations of the main production structures is provided in Appendix A.

Bilateral trade is specified following the Armington's differentiated goods approach, where domestic and foreign goods are distinguished by origin (Armington 1969). The exception is the international market for crude oil, which we assume is perfectly homogenous. All goods used on the domestic market in intermediate and final demand correspond to a CES composite that combines the domestically produced good and the imported good from other regions. A balance of payment constraint incorporates the base-year trade deficit or surplus for each region.

CO_2 emissions are linked in fixed proportions to the use of fossil fuels, with CO_2 coefficients differentiated by the specific carbon content of fuels. Restrictions to the use of CO_2 emissions in production and consumption are implemented through exogenous emission constraints or (equivalently) CO_2 taxes. CO_2 emission abatement then takes place by fuel switching (inter-fuel substitution) or energy savings (either by fuel-non-fuel substitution or by a scale reduction of production and final demand activities).[3]

We determine the free parameters of the functional forms (i.e., cost and expenditure functions) such that the economic flows represented in the base-year data are consistent with the optimizing behavior of the model agents. The base-year data stems from the GTAP 8 database which includes detailed national accounts on production and consumption (input-output tables) together with bilateral trade flows and CO_2 emissions for up to 129 regions and 57 sectors for the year 2007 (Narayanan G., Aguiar and McDougall 2012).

The responses of agents to price changes are determined by a set of exogenous elasticities taken from the pertinent econometric literature. Elasticities in international trade come from the estimates included in the GTAP database. Substitution elasticities between the production factors capital, labor, energy inputs and non-energy inputs (materials) are taken from Okagawa and Ban (2008). The elasticities of substitution in fossil fuel sectors are calibrated to match exogenous estimates of fossil-fuel supply elasticities (Graham, Thorpe and Hogan 1999, Krichene 2002).

In our analysis, we adopt the 2007 baseline described in the GTAP dataset as the pre-policy equilibrium against which we compare the effects of policy regimes. We aggregate the 57 sectors provided by the GTAP database into 13 sectors. The energy goods identified are coal, crude oil, natural gas, refined oil products, and electricity which allows us to distinguish energy goods by CO_2 intensity and to capture the potential for fossil-fuel switching. Furthermore, we consider a variety of energy-intensive (non-energy) commodities that are most exposed to unilateral climate policies: chemical products; mineral products; iron and steel; non-ferrous metals; air, land and water transports. At the regional level, we represent 9 major world regions meant to represent the major players in international climate policy negotiations.

[3] Revenues from emission regulation accrue either from CO_2 taxes or from the auctioning of emission allowances (in the case of a grandfathering regime) and are recycled lump sum to the representative agent in the respective region.

	REGIONS
Coalition	United States; EU-27 plus European Free Trade Area; Other Annex I without Russia (Canada, Japan, Belarus, Ukraine, Australia, New Zealand, Turkey)
Non-Coalition	China and Hong Kong; India; Russia; Other Energy-Exporting Countries; Other Middle-Income Countries; Other Low-Income Countries
	SECTORS
Energy	Coal; Crude Oil; Natural Gas; Refined Petroleum*; Electricity
Energy-intensive	Chemical, Rubber and Plastic Products*; Iron and Steel*; Non-Ferrous Metal*; Non-Metallic Mineral*; Water Transport; Air Transport; Other Transport
Other	All Other Goods

* — Indicates energy-intensive and trade-exposed (EITE) sectors that are the subject of the carbon tariffs and countervailing measures.

Table 1: Regions and Sectors in the Aggregated Dataset

Table 1 provides a list of sectors and regions for the composite dataset underlying our analysis. In our experiments, we assume that there is a coalition of countries that reduce their domestic carbon emissions and consider the use of carbon tariffs against non-coalition countries. Our default assumption is that the coalition includes all countries identified as Annex-I members under the Kyoto Protocol minus Russia.[4] The coalition or non-coalition membership is indicated in the table. The carbon tariffs and the retaliatory measures used by non-coalition members that are the subject of the policy scenarios are limited to a set of energy-intensive and trade-exposed (EITE) goods that, in practice, have received the most attention from policymakers as potential objects of regulation. The EITE sectors are indicated with the "*" symbol in the table. The mappings of regions and sectors from the fully disaggregate GTAP dataset to our aggregation are described in Appendix B.

Table 2 reports the 2007 benchmark GDP, carbon emissions and carbon intensity levels by region from the GTAP data. Two patterns emerge from the data. First, coalition regions are

[4]Russia was a signatory to the Kyoto Protocol primarily because abatement targets were defined relative to 1990 emission levels. Russia's economic collapse meant that their unregulated emission levels fell dramatically, such that Russia had the potential benefit from signing the agreement by selling off unused emission permits to other carbon-constrained countries even if no abatement measures were ever undertaken in Russia itself.

	CO_2	GDP	CO_2 Intensity
Coalition			
United States	5.58	14060.93	0.39
Other Annex-I	2.59	7631.75	0.34
Europe	4.15	17846.81	0.23
Non-Coalition			
China	5.18	3696.53	1.39
Russia	1.42	1299.67	1.09
India	1.30	1232.35	1.05
Other Low-Income	0.65	733.82	0.88
Other Energy-Exporting	1.92	2414.06	0.80
Other Middle-Income	3.45	6879.37	0.50

* — CO_2 measured in billions of metric tons; GDP measured in billions of US dollars 2007; CO_2 intensity measured in metric tons per thousand dollars.

Table 2: Benchmark Economic and Emission Statistics by Region

large in terms of the amount of output they contribute to the world economy — collectively they represent over 70% of world output. As a result, they are likely to influence international prices by implementing unilateral emission regulation — both through the choice of how much domestic abatement to pursue and through the decision to employ carbon tariffs. Second, while they also contribute a substantial fraction of world carbon emissions (approximately 45%) they are significantly less carbon intensive per dollar of ouput produced. Among non-coalition regions, China and Russia stand out as the two most carbon-intensive regions.

3 Policy Game

We assume that — in the absence of any emission or policy response from non-coalition countries — coalition countries collectively agree to reduce their emissions by 20% using a uniform carbon tax (or a system of tradable emission permits) across all sectors and regions within the coalition. This is a commitment broadly consistent with the targets negotiated under the Kyoto Protocol. It translates into a global abatement rate of approximately 10% relative to pre-policy base year emissions levels.

Figure 1 depicts the structure of our policy game. Both coalition members and non-coalition countries are assumed to realize the implications of the policy actions of all players for the general equilibrium adjustments in the world economy. The coalition chooses either to use carbon tariffs against unregulated non-coalition countries (Tariff) or not (No Tariff). With knowledge of the coalition's choice, all non-coalition regions simultaneously choose their response. On the No-Tariff branch of the game tree, a non-coalition region may choose either to cooperate and adopt regional emission restrictions or do nothing and leave its emissions unregulated. On the Tariff branch of the tree, a non-coalition region may choose between the two options just described as well as the option to retaliate (strategy labelled "R" in the figure) by raising its import tariffs against coalition members and leaving its emissions unregulated. On the Tariff branch of the tree, a non-coalition country is subject to carbon tariffs unless they choose cooperation, in which case the tariffs are removed. The policy responses available to non-coalition countries are described in more detail below.

Cooperate (C) — the non-coalition region restricts domestic emissions by an amount equal (as a percentage of its pre-policy baseline emissions) to the reductions undertaken by the coalition. Non-coalition abatement takes place via a regional carbon tax that is uniform across all of the region's sectors (or, equivalently, a regional system of tradable emission permits).

Retaliate (R) — the non-coalition region raises a uniform import tariff on EITE goods from all coalition countries such that the added revenue generated by this tariff equals the revenue generated by the carbon tariffs imposed on them. It continues to operate with unrestricted emissions.

Do Nothing (D-N) — the non-coalition region operates with unrestricted emissions.

When coalition countries employ carbon tariffs, the tariff rates are levied on the carbon emissions embodied in EITE imports from non-coalition countries. In our simulations, embodied emissions compromise direct emissions (those emerging from the combustion of fossil fuels in EITE production) as well as indirect emissions from electricity inputs (i.e., emissions caused by the generation of electricity which is used in EITE production). It is straightforward to calculate these emissions from the multi-region, multi-sector GTAP dataset (Böhringer et al. 2011). The effective carbon tariffs then emerge as the product of the emission price in coalition countries and the embodied (sector- and region-specific) carbon content of the imported goods.

When non-coalition countries choose to retaliate, they calculate their countervailing tariff rates (uniform across sectors and coalition countries) such that the value of the tariff revenues equal the value of the revenues by the carbon tariffs imposed by coalition countries on them.

A number of assumptions underlying the policy scenarios deserve further discussion. First, we hold global emissions constant across all of the policy scenarios. This accommodates the coherent cost-effectiveness comparison of alternative policy regimes without the need to evaluate

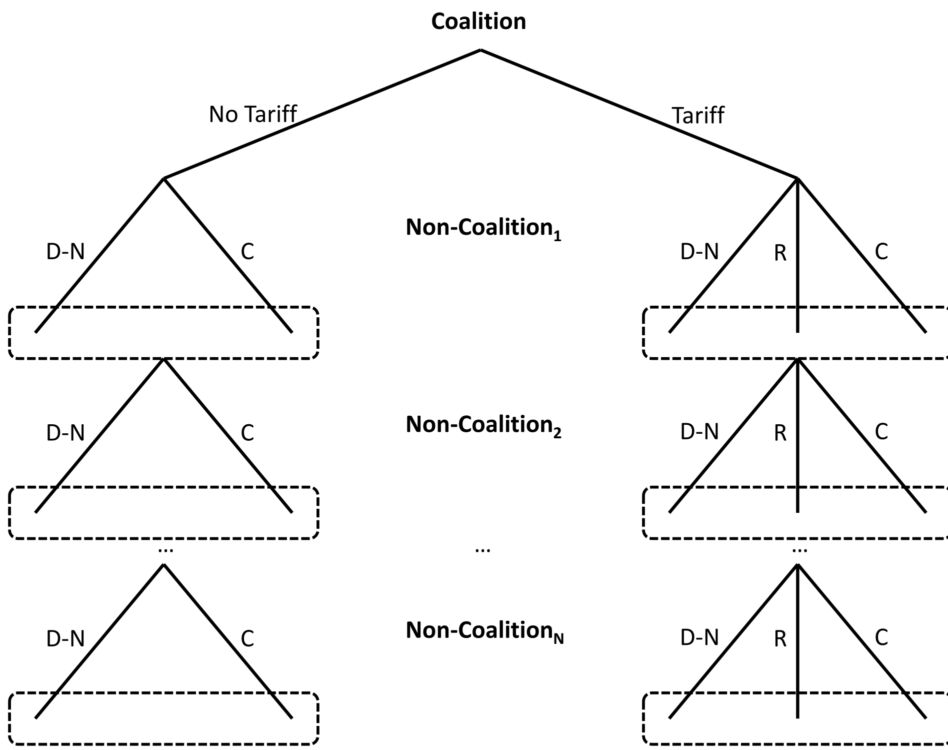

Figure 1: Structure of the Policy Game

the (rather uncertain) external costs of CO_2 emissions. There is also a behavioral rationale for holding global emissions constant. Ultimately, the outcome of interest is the non-cooperative determination of global abatement levels. Climate services are a global public good. A central prediction of models dealing with the voluntary provision of public goods is that substantial crowding out of individual contributions will occur when the aggregate supply of the public good increases (Bergstrom, Blume and Varian 1986). In our context, the rational response of coalition countries to increased levels of abatement in non-coalition countries is to curtail their effort. Holding global emissions constant amounts to assuming that there is full crowding out of Annex-I contributions to the public good when non-Annex-I countries increase their contributions.[5]

Second, coalition countries set carbon-tariff rates based on direct emissions from the burning of fossil fuels in the production of imported goods as well as the indirect emissions embodied in the electricity inputs to that production process. There are a variety of assumptions represented in the literature on border carbon adjustments ranging from the use of just direct

[5]A caveat here is that models of the voluntary provision of public goods typically assume that agents are unable to affect the price of contributing to the public good with their choice of contribution level. In our scenario, the price will depend on the performance of regional economies.

emissions (Mattoo et al. 2009) to the use of the full direct and indirect emissions embodied in goods (Böhringer et al. 2011). The measure we use here, direct emissions plus emissions from electricity inputs, here is a compromise. It is significantly more comprehensive than using just direct emissions since electricity is an important, carbon-intensive input to many traded goods. However, it is also simple enough to implement (as opposed to those metrics based on the full input-output measures).

Third, retaliation in our policy game means raising a uniform tariff on imports from coalition countries equal in value to the carbon tariffs placed on the retaliating country. This assumption is meant to capture the spirit of the retaliatory measures allowable under the World Trade Organization (WTO) when a country is faced with a trade barrier the WTO deems illegal. Similarly, both the carbon tariffs and the countervailing measures are limited to a set of energy-intensive, trade-exposed goods (described in Table 1). It should be acknowledged, however, that alternative designs for the tariffs result in different potency, which could make cooperation from non-coalition countries either more or less likely.

Fourth, cooperation from non-coalition countries means taking on abatement responsibilities equal (as a percentage reduction from baseline emissions) to the abatement undertaken in coalition countries in equilibrium. We also assume that non-coalition regions do not have access to trade in emission permits with each other or with coalition countries. While the specific requirement that abatement rates should be equal might appear arbitrary, it represents a strong impediment to sustaining cooperation from non-coalition countries as it assigns far more abatement responsiblity to these countries than current international climate negotiations are pursuing. If non-coalition countries can justify equilibrium abatement at this level, it is likely that cooperation in regimes with more modest commitments would be sustainable as well. Similarly, prohibiting access to international permit trade for these countries tends to raise the cost of participation. It also responds to concerns in the climate-policy debate regarding the feasibility of including developing-world regions in unrestricted emission trading systems. As we will see in our simulation analysis, if major non-coalition countries can be included without cost in unrestricted emissions trade then the rationale for carbon tariffs largely disappears.

Fifth, we have chosen to aggregate a number of the smaller non-coalition countries into larger regions that choose their policy strategies as unitary actors. For example, the countries summarized within the composite Other Energy-Exporting region then act collectively. While this assumption may exaggerate the power of both the decision to adopt emission controls and the decision to use tariffs in retalition against the carbon tariffs used by the coalition, the alternative is to disaggregate these countries and solve for their strategies separately. The difficulty here is that this would increase the dimensionality of the policy game substantially.[6] As we

[6] In the game's current configuration, we must compute payoffs for over 700 different policy regimes to get the required payoff structure to solve the game. This is computationally time consuming. Moreover, this number increases as an exponential function of the number of non-coalition regions in the model.

show in the discussion of the results of our experiments, however, these countries do not appear to be key players in determining the character of the Nash equilibrium outcomes, so this assumption is unlikely to be an important driver of our main results.

4 Results

Table 3 reports the welfare effects of key policy regimes. Welfare impacts are defined as Hicksian equivalent variation in income as a percentage of the pre-policy equilibrium levels. A positive number in the table represents a welfare loss (i.e. a positive cost) and a negative number a welfare gain.[7]

	Tariff		**No Tariff**		Unrestricted
	CHN,RUS=C Others=R*	All D-N	All D-N*	All C	Int'l Permit Trade
	(1)	(2)	(3)	(4)	(5)
All	0.19	0.39	0.41	0.12	0.08
Coalition	0.08	0.23	0.33	-0.01	0.06
Non-Coalition	0.48	0.87	0.65	0.49	0.14
	Coalition				
Europe	0.10	0.28	0.41	-0.02	0.03
United States	0.02	0.08	0.14	-0.02	0.08
Other Annex-I	0.20	0.45	0.57	0.04	0.11
	Non-Coalition				
China	0.25	0.44	0.16	0.12	-0.41
Russia	1.66	2.83	2.08	1.59	0.83
India	-0.21	-0.31	-0.44	-0.22	-0.34
Other Energy-Exporting	1.89	3.32	2.91	2.02	1.20
Other Middle-Income	0.09	0.23	0.15	0.10	-0.02
Other Low-Income	0.37	0.56	0.43	0.63	0.33

Notes: * — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime; CHN=China, RUS=Russia, C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 3: % Welfare Loss by Region and Policy Regime

In the unique Nash equilibrium prediction from the model, China (CHN) and Russia (RUS) cooperate (C) by adopting emission targets and all other non-coalition regions retaliate (R)

[7] The welfare measures for the aggregated regions are based on a utilitarian social welfare function which is agnostic about the distribution of the costs or benefits within the region.

against the carbon tariffs with import tariffs imposed on coalition countries. This outcome is listed in column (1). We compare this outcome to a number of benchmarks. As measure of the potential for the carbon tariffs to benefit coalition states and punish non-coalition states, we include the regime in which all non-coalition states choose to remain unregulated — the "Do Nothing" (D-N) outcome — despite being subjected to carbon tariffs by the coalition (column 2). We compare this with the regime where all non-coalition countries continue to "Do nothing" but where the coalition does not use the carbon tariffs (column 3). This outcome also represents the best response of non-coalition countries if the coalition were to choose not to use the tariffs. Therefore, coalition countries use the payoffs associated with this outcome to determine the returns to using the tariffs. As one measure of the potential efficiency gains associated with cooperation, we also report the regime in which all non-coalition countries choose to cooperate (column 4). The cooperative outcome described in (4) will not, in general, produce the minimum-cost method of reaching the abatement target and, therefore, underestimates the full efficiency gains that could theoretically be obtained from cooperation (recall that cooperating non-coalition countries undertake domestic abatement without trading emission permits internationally). As a second measure of the potential for efficiency gains in abatement, we report the equilibrium outcome in which all world regions face a uniform carbon tax or, equivalently, participate in an system of unrestricted international emission permit trade (column 5). This outcome represents the minimum-cost strategy for meeting the global abatement target. The assumption regarding the burden sharing in this scenario is that countries are allocated emission permits sufficient to cover 80% of their benchmark emissions for coalition countries and 100% of their benchmark emissions for non-coalition countries. Thus non-coalition countries are compensated for their direct abatement costs by transfers from coalition countries (note, however, that they may experience other gains or losses due to the general equilibrium adjustments such as terms-of-trade changes).

In the Nash equilibrium where China and Russia cooperate while the remaining noncoalition countries retaliate, the 10% reduction in global carbon emissions comes at cost of 0.19% of global welfare. Compared to the outcomes where no non-coalition regions participate in abatement, the cooperation from China and Russia reduces the cost of achieving the target from 0.41% when coalition countries do not employ carbon tariffs (3) or 0.39% when they do use the tariffs (2). The cost under full cooperation (4) is 0.12%. Thus the Nash equilibrium outcome captures approximately three-quarters of the possible efficiency gains measured against our cooperative benchmark or approximately two-thirds of the gains attainable by the cost-minimizing first-best regime in (5). The overall cost of the policy is lower when non-coalition countries take on abatement responsibility because these countries are the source of low-cost abatement opportunities (as suggested by Table 2): shifting abatement to these countries moves the policy toward the first-best outcome.

In the Nash equilibrium, the costs of abatement fall more heavily on the non-coalition countries (0.48%) than the coalition (0.08%). This distribution reflects the fact that China and Russia take on abatement responsibilities in this policy regime. However, comparing this outcome to column (3), in which the coalition is responsible for all abatement, it is clear that abatement is costly for non-coalition countries (0.65%) even when they do not undertake it themselves. This is due primarily to the fact Russia and Other Energy-Exporting countries suffer from the depressing effect that abatement has on demand and prices for their exports of energy and energy-intensive goods. Other non-coalition regions experience relatively small, negative changes in welfare compared to the pre-policy benchmark equilibrium.[8]

Comparing columns (2) and (3) provides a measure of the impact when coalition countries impose carbon tariffs on non-coalition countries. Coalition regions uniformly benefit from the use of the tariffs as they allow these countries to capture terms-of-trade gains; on the other side, non-coalition countries (except for India) uniformly lose with major energy suppliers (Russia and Other Energy-Exporting) suffering the most in percentage terms. Global welfare cost of abatement decline only from 0.41% to 0.39% when tariffs are used. Thus embodied carbon tariffs are not particularly effective as a means to directly reduce the global cost of abatement.

The regime described in (3) represents the best response for non-coalition countries if the coalition fails to employ the tariffs. Energy-importing non-coalition countries (China, India, Other Middle-Income and Other Low-Income) would prefer this outcome to the Nash equilibrium primarily because energy imports become cheaper, but energy exporters prefer the latter for the same reason. However, coalition countries uniformly prefer to use the tariffs — in part because of the rents they capture from using them and in part because the cooperation it induces from China and Russia relieves them of a substantial share of the abatement burden to meet the global emission reduction target.

The comparison of (2) and (3) makes clear that the tariffs have a measurable punitive effect on many of the non-coalition countries. However, the comparison of (3) and (4) also makes clear that the net effect of changes to the terms of trade plays an important role in shaping the equilibrium outcome. China, Russia and the Other Energy-Exporting region all experience welfare gains moving from the unregulated outcome in (3) to the fully cooperative outcome in (4), implying that these sources of economic gains are strong enough to offset the direct costs of abatement in these regions.

Finally, we compare (1) with (5), the benchmark calculation in which there is a global system of international trade in emission permits and non-coalition countries receive compensation via the assumption that their initial holdings of permits are sufficient to cover 100% of their baseline emissions. As noted before, the equilibrium in (5) represents a minimum-cost method

[8]The exception is India which benefits when the coalition takes on more abatement. This is because it experiences a strong terms-of-trade effect in the form of lower prices on fossil energy imports when abatement takes place. This effect is more pronounced when coalition countries undertake more abatement because the cost of the abatement policy is higher.

	Deviation	Welfare Change
China	Retaliate	0.06
	Do Nothing	0.08
Russia	Retaliate	0.01
	Do Nothing	0.01
India	Cooperate	0.06
	Do Nothing	—
Other Energy-Exporters	Cooperate	0.34
	Do Nothing	0.02
Other Middle-Income	Cooperate	0.06
	Do Nothing	0.03
Other Low-Income	Cooperate	0.33
	Do Nothing	—

Table 4: Percentage-Point Welfare Cost of Deviation from Nash Equilibrium

of achieving the global abatement target. We would expect it to dominate all other policy regimes in aggregate welfare terms. The aggregate cost of the policy is 0.08% or slightly less than half the cost of the Nash equilibrium policy regime. Both coalition and non-coalition regions benefit with most of the gains going to non-coalition countries.[9] This is because the burden-sharing rule assumed implies large wealth transfers to these countries in exchange for their abatement services.

Table 4 describes the welfare losses non-coalition countries experience when they unilaterally deviate from their Nash equilibrium strategy. Welfare losses are calculated as percentage-point differences from the welfare changes obtained in the Nash equilibrium. China and Russia both cooperate in equilibrium. Retaliating with higher import tariffs of their own benefits China relative to doing nothing. However, both policies would generate moderate welfare losses relative to cooperation. Russia registers a modest welfare loss if they follow either alternative policy. Cooperation appears costly for most of the non-coalition regions that choose to retaliate in equilibrium — particularly energy-exporting and low-income countries. The "Do Nothing" option, is less costly, suggesting that these countries choose not to cooperate mainly to avoid abatement costs as opposed to capturing rents from their countervailing tariffs.

Table 5 reports on the emission changes as a percentage of pre-policy base-year emission levels. The prevailing price of carbon emissions (measured in 2007 US Dollars per ton of CO_2)

[9]The exception is the United States which is slightly worse off under (5).

	Tariff		No Tariff		Unrestricted
	CHN,RUS=C Others=R*	All D-N	All D-N*	All C	Int'l Permit Trade
	(1)	(2)	(3)	(4)	(5)
All	9.39	9.39	9.39	9.39	9.39
Coalition	13.58	21.37	22.01	9.39	6.22
Non-Coalition	5.68	-1.21	-1.78	9.39	12.20
	Coalition				
Europe	10.32	16.80	17.43	6.75	4.37
United States	16.41	25.26	25.88	11.75	7.91
Other Annex-I	12.71	20.30	20.99	8.53	5.52
	(27.39)	(55.82)	(57.66)	(17.61)	(10.58)
	Non-Coalition				
China	13.58	-0.23	-0.75	9.39	18.85
	(6.89)	—	—	(4.51)	(10.58)
Russia	13.58	-0.54	-2.25	9.39	7.98
	(20.29)	—	—	(13.06)	(10.58)
India	-0.90	-1.07	-1.47	9.39	17.09
	—	—	—	(5.20)	(10.58)
Other Energy-Exporting	-1.06	-1.45	-2.01	9.39	5.25
	—	—	—	(20.20)	(10.58)
Other Middle-Income	-1.80	-2.69	-2.93	9.39	7.01
	—	—	—	(15.37)	(10.58)
Other Low-Income	-1.68	-2.29	-2.84	9.39	6.65
	—	—	—	(15.91)	(10.58)

Notes: * — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime; CHN=China, RUS=Russia, C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 5: % Emission Reduction by Region and Policy Regime

in each region and policy regime is listed in parentheses directly below the emission entries in the table. As noted before, the coalition's commitment to reducing their domestic emissions by 20% translates into an approximately 9% reduction in global emissions. When all non-coalition countries remain unregulated and the coalition does not employ tariffs (3), non-coalition emissions rise by approximately 2%. This corresponds to a global leakage rate of approximately 9%.[10]

The effect of the carbon tariffs on leakage can be seen from (2). Leakage falls by roughly a third due to the tariffs, an effect that relieves coalition countries of approximately 3% of their abatement responsibility relative to (3). The tariffs are particularly effective at controling leakage to Russia (through their dampening effect on Russia's energy-intensive exports) which goes from increasing its emissions by 2.25% under (3) to 0.54% under (2).

In the Nash equilibrium (1), China and Russia take on approximately almost 40% of the coalition's abatement responsibilities relative to (3). Leakage to other non-coalition countries falls relative to the carbon-tariff benchmark in (2). The prevailing carbon prices in China, Russia and the coalition in the Nash equilibrium show that abatement costs are significantly lower in China and Russia – particularly in China. These countries reduce their emissions by approximately 14% at a marginal abatement cost of \$7 per ton in China and \$20 per ton in Russia. The same reduction in coalition countries implies a marginal abatement cost of \$27 per ton.

To summarize our main results, we find that the non-cooperative equilibrium in our policy game supports cooperation from China and Russia. These countries are large enough sources of relatively low-cost abatement that this results in substantial global cost savings to achieve the global abatement target. Their cooperation is supported by a combination of two effects. First, facing carbon tariffs is damaging to these countries. Second, the improvement in the performance of world economy when abatement shifts from high-abatement-cost coalition countries to these comparatively low-cost countries benefits them as well. Both factors lower the opportunity cost of cooperation. Other non-coalition regions generally find abatement too expensive to justify cooperation — particularly given that they can free ride on the efforts of China and Russia.

5 Sensitivity Analysis

5.1 Trade and Fuel-Supply Elasticities

There are two sets of parameter values to which the results of CGE analyses of unilateral carbon policies consistently prove sensitive. First, the Armington elasticities that govern the ease of substitution between varieties of the same good produced in different countries are important.

[10]The leakage rate is defined as the ratio of the emission change in non-coalition countries over the emission change in coalition countries.

For example, the Armington elasticities affect the degree to which the world's consumers can look elsewhere for emission-intensive goods when the varieties they would have purchased from coalition countries become more expensive under the carbon policy. They also impact the terms-of-trade advantage a country can expect to gain by using tariffs. When these elasticities take on smaller values, export supply of a given country's product is less elastic, implying a higher optimal tariff.

Second, the values of the supply elasticities of fossil energy goods will affect the uptake in energy demand in unregulated countries when carbon policies come into place. A lower elasticity value implies a larger drop in the price of an energy good when its demand in regulated countries falls under the carbon policy. This leads to larger welfare losses for energy-exporting regions.

Table 6 describes the results of sensitivity analysis in which we double and halve the Armington and fuel supply elasticities. In each case the elasticity values are changed simultaneously for all regions and goods. Thus a row entry in the table labelled "2x" in the Armington elasticity column is interpreted as doubling all of the Armington elasticities from the reference levels that were the basis of the experiments described in the previous section. Similarly, supply elasticities for coal, natural gas and crude oil are doubled or halved for all three goods in all regions in the model simultaneously. The first two columns of the table describe the elasticity assumptions. Columns 3-8 indicate the Nash equilibrium strategy chosen by each non-coalition country in a particular experiment. The final three columns report the welfare effects associated with the Nash equilibrium.

Armington	Fuel Supply	**Regional Strategy**						**Welfare Change**		
Elasticity	Elasticity	CHN	RUS	IND	EEX	MIC	LIC	All	Coalition	Non-Coalition
1/2x	2x	C	C	R	C	C	R	0.13	0.01	0.49
	1x	C	C	R	R	C	R	0.15	-0.01	0.59
	1/2x	C	C	R	R	C	R	0.14	-0.06	0.72
1x	2x	C	R	R	R	R	R	0.21	0.14	0.41
	1x	C	C	R	R	R	R	0.19	0.08	0.48
	1/2x	C	C	R	R	R	R	0.19	0.05	0.58
2x	2x	C	D-N	D-N	R	R	R	0.22	0.18	0.35
	1x	C	C	D-N	R	R	R	0.20	0.13	0.41
	1/2x	C	C	D-N	R	R	R	0.20	0.10	0.49

Notes: CHN=China, RUS=Russia, IND=India, EEX=Other Energy-Exporting countries, MIC=Other Middle-Income countries, LIC=Other Low-Income countries, C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 6: Equilibrium Outcome and Welfare Change Sensitivity Analysis

Our finding that China cooperates in equilibrium is robust to the alternative elasticity assumptions. In many of the sensitivity runs, Russia also continues to cooperate, but its participation is clearly more fragile. Specifically, when fuel-supply elasticities are doubled it no longer chooses to cooperate. The intuition is that when fuel supply is more elastic, Russia no longer stands to lose as much revenue from depressed fuel prices under unilateral abatement by the coalition. Therefore, the gains to cooperating are smaller. The global welfare implications of the equilibrium outcome are also stable. When Armington elasticities are halved, Middle-Income countries and, in some cases, countries in the Other Energy-Exporting region join China and Russia in taking on abatement responsibilities. When the Armington elasticities are low, the carbon tariffs have a more punishing effect, which promotes cooperation. When Armington elasticities are doubled, India no longer retaliates and simply remains unregulated.

Table 7 examines in more detail how the incentives for China to cooperate are altered in the sensitivity analysis. The table reports the welfare cost for the country associated with deviating from its equilibrium strategy, the same metric explored in Table 4. Note that we report here only the sensitivity cases in which we vary one set of parameters (either Armington or fuel supply elasticities) while holding the other at its reference levels.

	Do Nothing	Retaliate
Armington Elasticity		
2x	0.09	0.11
1x	0.08	0.06
1/2x	0.10	0.07
Fuel Supply Elasticity		
2x	0.13	0.11
1x	0.08	0.06
1/2x	0.04	0.02

Table 7: Percentage-Point Welfare Cost of Deviation for China: Sensitivity Analysis

In most of the scenarios, China faces measurable penalties if it deviates. The exception is when fuel supply elasticities are assumed to be half as elastic as in the central case scenario. China is a large net energy importer. As a result, cooperation tends to be less valuable to that country when energy supply elasticities are low. The intuition is that China benefits from the lower price of energy imports when the coalition abatement depresses world energy markets. If this effect were strong enough, China might prefer to leave abatement in the hands of coalition countries. In this case it would lose the terms-of-trade benefits it gets from stronger demand for its exports in coalition countries but it would gain the benefits of cheap energy imports.

	Tariff		No Tariff	
	CHN,RUS=C IND=D-N Others=R*	CHN=C Others=D-N	CHN=C Others=D-N*	All C
	(1)	(2)	(3)	(4)
All	0.06	0.07	0.08	0.03
	Coalition			
Europe	0.09	0.10	0.13	—
	Non-Coalition			
China	0.16	0.21	0.22	0.03
Russia	0.60	0.66	0.46	0.47
United States	-0.03	-0.03	-0.03	-0.01
Other Annex-I	-0.02	—	—	—
India	-0.04	-0.04	-0.06	-0.07
Other Energy-Exporting	0.58	0.63	0.51	0.59
Other Middle-Income	0.05	0.07	0.05	0.02
Other Low-Income	0.12	0.12	0.08	0.18

Notes: * — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime; CHN=China, RUS=Russia, IND=India, C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 8: % Welfare Loss by Region and Policy Regime: Europe-Alone Coalition

5.2 Coalition Size

Our main results rely on the assumption that all Annex-I countries are committed to reducing at a level roughly consistent with their Kyoto-Protocol targets. To explore the implications of relaxing this assumption, we examine the results of an alternative coalition structure where Europe (EU-27 plus EFTA) is the only coalition member in Table 8. The United States and Other Annex-I countries join the group of non-coalition countries. Thus Europe is now the only source of carbon tariffs and the United States and Other Annex-I countries are potentially on the receiving end of these tariffs. The table reports the key policy regimes and welfare effects in the same manner as Table 3.

The Nash equilibrium prediction, once again, involves China and Russia adopting abatement targets while other non-coalition countries retaliate against the carbon tariffs from Europe. The exception is India, which chooses not to retaliate. The United States and Other Annex-I countries generally benefit from Europe's abatement, so they are not inclined to adopt abatement targets of their own. The best response from non-coalition countries when Europe chooses not to employ carbon tariffs differs from our earlier experiments however. China continues to find it in its best interest to cooperate in spite of the fact that it faces no threat of the tariffs. Thus the terms-of-trade shift in the world economy when abatement allocation moves to China appears to be strong enough to justify cooperation on its own. Because of this, the gains from using the tariffs are smaller. By design, the reduction in world emissions (a 20% reduction in Europe's emissions translates into roughly a 3% reduction in world emissions) is smaller in this experiment than in our core simulations, so all of the welfare differences between the policy regimes appear smaller. In conclusion, cooperation is still sustainable with a smaller coalition of commited countries, but the stakes for cooperation are lower here as well.

5.3 Coalition Crowding-Out Effects

Our main results are obtained under the assumption that the coalition of Annex-I countries reduce their abatement one-for-one when non-coalition countries take on more of the responsibility in the Nash equilibrium. Here we explore the consequences of assuming that no crowding out takes place. That is, we assume that the level of abatement that takes place within the coalition is constant across the different policy scenarios we consider. The welfare effects of these policies are not comparable to those described in our main experiments without parameterizing marginal benefits of abatement curves for the regions in our model because the global abatement levels will differ. We can, however, explore how much additional abatement the coalition can elicit from non-coalition countries through the punishment of the carbon tariffs.

Table 9 models this scenario by assuming that the coalition reduces its emissions by 20% below base-year levels regardless of what changes in emission levels take place outside of the coalition. We have run experiments in which we raised the abatement commitment for cooperation by non-coalition countries from 0% to 20% of base-year emissions at five-percentage-point intervals. The maximum level of commitment at which cooperation is sustainable as an equilibrium outcome is when non-coalition countries are required to reduce their base-year emission levels by 10%. The results of this simulation are shown in the table. Once again, the Nash equilibrium involves China and Russia adopting abatement targets. India also chooses to cooperate. All other regions retaliate. This raises global abatement from approximately 9% when only the coalition abates to approximately 15%. China and Russia still register significant gains relative to the case where they are subjected to the tariffs (column 2). However, the benefits the coalition experiences are nearly exhausted relative to the case where they decide not to use the tariffs. (This is, of course, ignoring the environmental benefits of the abatement they receive). Thus, it is the coalition's willingness to use the tariffs that is the limiting factor in sustaining the equilibrium.

	Tariff		No Tariff	
	CHN,RUS,IND=C Others=R*	All D-N	All D-N*	All C
	(1)	(2)	(3)	(4)
All	0.36	0.35	0.34	0.38
Coalition	0.24	0.19	0.26	0.20
Non-Coalition	0.70	0.78	0.57	0.91
	Coalition			
Europe	0.29	0.23	0.32	0.24
United States	0.09	0.06	0.11	0.07
Other Annex-I	0.45	0.39	0.47	0.40
	Non-Coalition			
China	0.20	0.40	0.13	0.22
Russia	2.22	2.58	1.83	2.91
India	-0.39	-0.29	-0.38	-0.48
Other Energy-Exporting	2.99	3.02	2.54	3.87
Other Middle-Income	0.17	0.21	0.13	0.21
Other Low-Income	0.56	0.51	0.38	0.98

Notes: * — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime; CHN=China, RUS=Russia, IND=India, C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 9: % Welfare Loss by Region and Policy Regime: No Annex-I Crowding Effect

5.4 Retaliation Option

Finally, we have assumed throughout that the retaliation option available to non-coalition countries is to impose comparable increases in tariffs on imports from coalition regions, where comparable is defined as increases in import-tariff rates on the same categories of goods that yield the same amount of tariff revenue as the carbon tariffs imposed on them by the coalition. This response is unlikely to represent an optimal response by non-coalition countries. First, a general pattern that emerges from the GTAP data is that non-coalition countries are sizable net exporters of embodied carbon emissions to coalition countries (Böhringer et al. 2011). Thus, the design of the retaliatory tariff in our central case experiments is such that it targets categories of goods that are not among those most heavily imported by these countries. Second, as a general rule higher optimal import tariffs should be placed on goods with more inelastic export supply (Limao 2008). Third, we constrain the retaliatory tariff rate to a revenue equivalent to the revenue raised by the coalition's carbon tariffs may mean that the tariff change is too low (or too high) relative to optimal levels.[11]

To explore the consequences of varying our assumptions on the design of retaliating tariffs, we have run two alternative specifications. In both cases, we assume that retaliatory tariffs are raised against all categories of imported goods (instead of just against EITE goods) and scaled inversely proportional to the Armington elasticities, consistent with the intersectoral pattern of optimal tariffs.[12] In one case, we maintain the assumption that the retaliatory tariff increases raise only as much revenue as the carbon tariffs themselves. In the other case, we assume that the increases in the tariffs rates are twice as large.

	Tariff		**No Tariff**	
	CHN=C Others=R*	All D-N	All D-N*	All C
	(1)	(2)	(3)	(4)
All	0.21	0.39	0.41	0.12
Coalition	0.13	0.23	0.33	-0.01
Non-Coalition	0.45	0.87	0.65	0.49
	Coalition			
Europe	0.15	0.28	0.41	-0.02
United States	0.05	0.08	0.14	-0.02
Other Annex-I	0.25	0.45	0.57	0.04
	Non-Coalition			
China	0.26	0.44	0.16	0.12
Russia	1.63	2.83	2.08	1.59
India	-0.21	-0.31	-0.44	-0.22
Other Energy-Exporting	1.87	3.32	2.91	2.02
Other Middle-Income	0.04	0.23	0.15	0.10
Other Low-Income	0.36	0.56	0.43	0.63

Notes: * — Indicates policy regime that represents a best response for all non-coalition countries for a given carbon tariff regime; CHN=China, C=Cooperate, D-N=Do Nothing, R=Retaliate.

Table 10: % Welfare Loss by Region and Policy Regime: Strong Retaliatory Tariff Option

The results of the first experiment show very little difference from the results of the central-case simulations reported in the paper. That is, the unique Nash equilibrium remains the one in which the coalition employs carbon tariffs, China and Russia adopt domestic emission controls,

[11] Optimal tariff rates can be quite high (approximately 60% on average based on the analysis of Ossa (2012)).

[12] For example, Broda, Limao and Weinstein (2008) show that the export supply elasticity a country faces can be expressed as an increasing function of the foreign supply elasticity, an increasing function of the average of other countries' demand elasticities (the Armington elasticities in our framework) and a decreasing function of the country's import share of the good.

and all other non-coalitions countries choose to retaliate. The effects on welfare and emission levels are similar as well. Table 10 displays the welfare effects for the case where the retaliatory tariffs raise twice as much revenue in the same format as for the previous simulations considered in the paper. In these experiments, Russia no longer finds it in its best interest to cooperate. As a result, the Nash equilibrium outcome in this scenario involves coalition countries employing the carbon tariffs, China adopting domestic emission controls, and all other countries — including Russia — choosing to retaliate. Despite the fact that Russia no longer chooses to adopt emission controls as an equilibrium strategy in this experiment the efficiency gains associated with the Nash equilibrium relative to the outcome where the coalition countries pursue abatement unilaterally are largely preserved. China absorbs a large fraction of the global abatement burden in our central-case scenarios when it decides to cooperate because it is a large, emission-intensive country. It also does so at substantially lower cost than the same amount of abatement pursue within the coalition. Russia is less of a critical player — it is a much smaller source of emissions and, therefore, does not cause significant global efficiency losses when it defects.

6 Conclusion

The issue of how to control emissions in large developing countries is central to the future of global warming policy. Without the participation of these countries, the costs of controling global emissions at levels consistent with avoiding "dangerous" climate interference will be very high if not prohibitively so. An assumption that seems to underlie much economic analysis of international climate policy is that the level of compensation required by developing countries to gain their participation in the near term is a political non-starter in countries that would be doing the compensation. In our analysis, the combined influence of carbon tariffs and international trade linkages in the global economy produce a different picture. Key developing countries already lose out when Annex-I countries abate even if they do no abatement of their own. This is primarily because they depend on the strong performance of Annex-I countries as destinations for their exports. In our analysis, this fact combined with the threat of the tariffs is enough to bring China and Russia into the fold.

There are a number of extensions to our assessment that would be useful to pursue in future research. Our analysis assumes that both the carbon tariffs that coalition countries use and the retaliatoty tariffs available to non-coalition countries are not optimally designed. While the alternative designs for the tariffs that we consider in section 5.4 mimic the sectoral pattern of optimal tariffs, true welfare-maximizing tariffs policy might be more potent tools than the ones we have described here — conferring either a greater ability to extract rents from trade partners or to damage them.

We assume that the global abatement target is held constant across policy regimes in our core analysis. We do this, in part, to facilitate welfare comparisons across regimes and, in part, to mimic the idea that voluntary effort to control climate change by coalition countries should be crowded out by increased non-coalition effort in a non-cooperative equilibrium. Alternatively, we could have specified formal preferences for climate services. For example, a common assumption in the trade and environment literature is that environmental quality is a normal good. In this case, the abatement that takes place in each policy regime would be endogenous to the changes they induce in the world economy. It is possible this could change the incentive for countries to cooperate. It would also be interesting to explore extensions of our analysis in which the share of abatement cooperating countries take on is endogenously determined.

Finally, the regional players in our policy game are aggregated to reduce the dimensionality of the computational problem at hand. As we have noted, this assumption confers an unrealistic degree of strategic influence to model regions comprised of many, smaller countries. It would be useful to reproduce our experiments using a more disaggregate model. It is worth noting, however, that the key players in sustaining the cooperative outcomes in our analysis, China and Russia, are represented as individual nations in our model. This gives us some confidence that our results are not driven by the effects of aggregation.

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A Algebraic Description of the CGE Model

The applied general equilibrium model is formulated as a system of nonlinear inequalities. The inequalities correspond to the two classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero profit) conditions for constant-returns-to-scale producers; and (ii) market clearance for all goods and factors. The former class determines activity levels and the latter determines price levels. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint and a commodity price to a market clearance condition.

In our algebraic exposition, the notation is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for constant-returns-to-scale production of sector i in region r where z is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's Lemma), which appear subsequently in the market clearance conditions. We use g as an index comprising all sectors/commodities i ($g = i$), the final consumption composite ($g = C$), the public good composite ($g = G$), and aggregate investment ($g = I$). The index r (aliased with s) denotes regions. The index EG represents the subset of all energy goods (here: coal, oil, gas, electricity) and the label FF denotes the subset of fossil fuels (here: coal, oil, gas). Tables 11 - 16 explain the notation for variables and parameters employed within our algebraic exposition. Figures 2 - 4 provide a graphical exposition of the production structure. Numerically, the model is implemented in GAMS (Brooke, Kendrick and Meeraus 1996) and solved using PATH (Dirkse and Ferris 1995).

Zero-profit conditions:

- Production of goods except fossil fuels ($g \notin FF$):

$$\Pi^Y_{gr} = p_{gr} - \left[\theta^M_{gr} p_{gr}^{M(1-\sigma^{KLEM}_{gr})} + (1-\theta^M_{gr}) \left[\theta^E_{gr} p_{gr}^{E(1-\sigma^{KLE}_{gr})} + (1-\theta^E_{gr}) p_{gr}^{KL(1-\sigma^{KLE}_{gr})} \right]^{\frac{(1-\sigma^{KLEM}_{gr})}{(1-\sigma^{KLE}_{gr})}} \right]^{1/(1-\sigma^{KLEM}_{gr})} \leq 0$$

- Sector-specific material aggregate:

$$\Pi^M_{gr} = p^M_{gr} - \left[\sum_{i \notin EG} \theta^{MN}_{igr} p_{igr}^{A(1-\sigma^M_{gr})} \right]^{1/(1-\sigma^M_{gr})} \leq 0$$

- Sector-specific energy aggregate:

$$\Pi^E_{gr} = p^E_{gr} - \left[\sum_{i \in EG} \theta^{EN}_{igr} (p^A_{igr} + p^{CO_2}_r a^{CO_2}_{igr})^{(1-\sigma^E_{gr})} \right]^{1/(1-\sigma^E_{gr})} \leq 0$$

- Sector-specific value-added aggregate:

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{K} v_{gr}^{(1-\sigma_{gr}^{KL})} + (1-\theta_{gr}^{K}) w_r^{(1-\sigma_{gr}^{KL})}\right]^{1/(1-\sigma_{gr}^{KL})} \leq 0$$

- Production of fossil fuels ($g \in FF$):

$$\Pi_{gr}^{Y} = p_{gr} - \left[\theta_{gr}^{Q} q_{gr}^{(1-\sigma_{gr}^{Q})} + (1-\theta_{gr}^{Q}) \left(\theta_{gr}^{L} w_r + \theta_{gr}^{K} v_{gr} + \sum_{i \notin FF} \theta_{igr}^{FF} p_{igr}^{A}\right)^{(1-\sigma_{gr}^{Q})}\right]^{1/(1-\sigma_{gr}^{Q})} \leq 0$$

- Armington aggregate:

$$\Pi_{igr}^{A} = p_{igr}^{A} - \left(\theta_{igr}^{A} p_{ir}^{(1-\sigma_{ir}^{A})} + (1-\theta_{igr}^{A}) p_{ir}^{IM(1-\sigma_{ir}^{A})}\right)^{1/(1-\sigma_{ir}^{A})} \leq 0$$

- Aggregagte imports across import regions:

$$\Pi_{ir}^{IM} = p_{ir}^{IM} - \left[\sum_{s} \theta_{isr}^{IM} (1+\tau_{isr}) p_{is}^{(1-\sigma_{ir}^{IM})}\right]^{1/(1-\sigma_{ir}^{IM})} \leq 0$$

Market-clearance conditions:

- Labor:

$$\bar{L}_r \geq \sum_{g} Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial w_r}$$

- Capital:

$$\bar{K}_{gr} \geq Y_{gr}^{KL} \frac{\partial \Pi_{gr}^{KL}}{\partial v_{gr}}$$

- Fossil fuel resources ($g \in FF$):

$$\bar{Q}_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial q_{gr}}$$

- Material composite:

$$M_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{M}}$$

- Energy composite:

$$E_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{E}}$$

- Value-added composite:

$$KL_{gr} \geq Y_{gr} \frac{\partial \Pi_{gr}^{Y}}{\partial p_{gr}^{KL}}$$

- Import composite:

$$IM_{ir} \geq \sum_g A_{igr} \frac{\partial \Pi^A_{igr}}{\partial p^{IM}_{ir}}$$

- Armington aggregate:

$$A_{igr} \geq Y_{gr} \frac{\partial \Pi^Y_{gr}}{\partial p^A_{igr}}$$

- Commodities ($g = i$):

$$Y_{ir} \geq \sum_g A_{igr} \frac{\partial \Pi^A_{igr}}{\partial p_{ir}} + \sum_{s \neq r} IM_{is} \frac{\partial \Pi^{IM}_{is}}{\partial p_{ir}}$$

- Private consumption ($g = C$):

$$Y_{Cr} p_{Cr} \geq w_r \bar{L}_r + \sum_g v_{gr} \bar{K}_{gr} + \sum_{i \in FF} q_{ir} \bar{Q}_{ir} + p^{CO_2}_r C\bar{O}_{2r} + \bar{B}_r$$

- Public consumption ($g = G$):

$$Y_{Gr} \geq \bar{G}_r$$

- Investment ($g = I$):

$$Y_{Ir} \geq \bar{I}_r$$

- Carbon emissions:

$$C\bar{O}_{2r} \geq \sum_g \sum_{i \in FF} E_{gr} \frac{\partial \Pi^E_{gr}}{\partial (p^A_{igr} + p^{CO_2}_r a^{CO_2}_{igr})} a^{CO_2}_{igr}$$

i, j	Sectors and goods
g	The union of produced goods i, private consumption C, public demand G and investment I
r, s, t	Regions
EG	Energy goods; coal, crude oil, refined oil, natural gas and electricity
FF	Fossil fuels; coal, crude oil and natural gas.

Table 11: Indices & Sets

Y_{gr}	Production of item g in region r
E_{gr}	Energy composite for item g in region r
KL_{gr}	Value-added composite for item g in region r
A_{igr}	Armington aggregate for commodity i for demand category (item) g in region r
IM_{ir}	Aggregate imports of commodity i in region r

Table 12: Activity Levels

p_{gr}	Price of item g in region r
p_{gr}^{M}	Price of material composite for item g in region r
p_{gr}^{E}	Price of energy composite for item g in region r
p_{gr}^{KL}	Price of value-added composite for item g in region r
p_{igr}^{A}	Price of Armington good i for demand category g in region r
p_{ir}^{IM}	Price of import composite for good i in region r
τ_{isr}	Tariff rate good i imported from region s to region r
w_r	Wage rate in region r
v_{ir}	Capital rental rate in sector i in region r
q_{ir}	Rent to fossil fuel resources in region r ($i \in FF$)
$p_r^{CO_2}$	Implicit price of carbon in region r

Table 13: Prices

$\bar{L}_r$	Aggregate labor endowment for region r
$\bar{K}_{ir}$	Capital endowment for sector i in region r
$\bar{Q}_{ir}$	Endowment of fossil energy resource i in region r ($i \in FF$)
$\bar{B}_r$	Initial balance for payment deficit or surplus in region r (note: $\sum_r \bar{B}_r = 0$)
$C\bar{O}_{2r}$	Aggregate carbon emission cap in region r
$a_{igr}^{CO_2}$	Carbon emission coefficient for fossil fuel i in demand category g in region r ($i \in FF$)

Table 14: Endowments and Carbon Emissions Specification

θ^{M}_{gr}	Cost share of material composite in production of item g in region r
θ^{E}_{gr}	Cost share of energy composite in the aggregate of energy and value added of item g in region r
θ^{MN}_{igr}	Cost share of material input i in the material composite of item g in region r
θ^{EN}_{igr}	Cost share of energy input in the energy composite of item g in region r
θ^{K}_{gr}	Cost share of capital within the value-added composite of item g in region r
θ^{Q}_{gr}	Cost share of fossil fuel resource in fossil fuel production ($g \in FF$) in region r
θ^{L}_{gr}	Cost share of labor in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ^{K}_{gr}	Cost share of capital in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ^{FF}_{igr}	Cost share of good i in non-resource inputs to fossil fuel production ($g \in FF$) in region r
θ^{A}_{igr}	Cost share of domestic output i within the Armington item g in region r
θ^{M}_{isr}	Cost share of exports of good i from region s in the import composite of good i in region r

Table 15: Cost Share Parameters

σ_{gr}^{KLEM}	Substitution between the material composite and the energy-value-added aggregate in the production of item g in region r*
σ_{gr}^{KLE}	Substitution between energy and the value-added composite in the production of item g in region r*
σ_{gr}^{M}	Substitution between material inputs within the energy composite in the production of item g in region r*
σ_{gr}^{KL}	Substitution between capital and labor within the value-added composite in the production of item g in region r*
σ_{gr}^{E}	Substitution between energy inputs within the energy composite in the production of item g in region r (by default $= 0.5$)
σ_{gr}^{Q}	Substitution between natural resource input and the composite of other inputs in the fossil fuel production ($g \in FF$) of region r***
σ_{ir}^{A}	Substitution between domestic variety and the composite of imported varieties from different regions for good i in region r**
σ_{ir}^{IM}	Substitution between imports from different regions within the import composite for good i in region r**

* — Calibrated based on estimates from Okagawa and Ban (2008).

** — Calibrated based on estimates from Narayanan G. et al. (2012) with the exception for elasticities in the market for crude oil which are assumed equal to $+\infty$.

*** — Calibrated based on estimates from Graham et al. (1999) and Krichene (2002).

Table 16: Elasticity Parameters

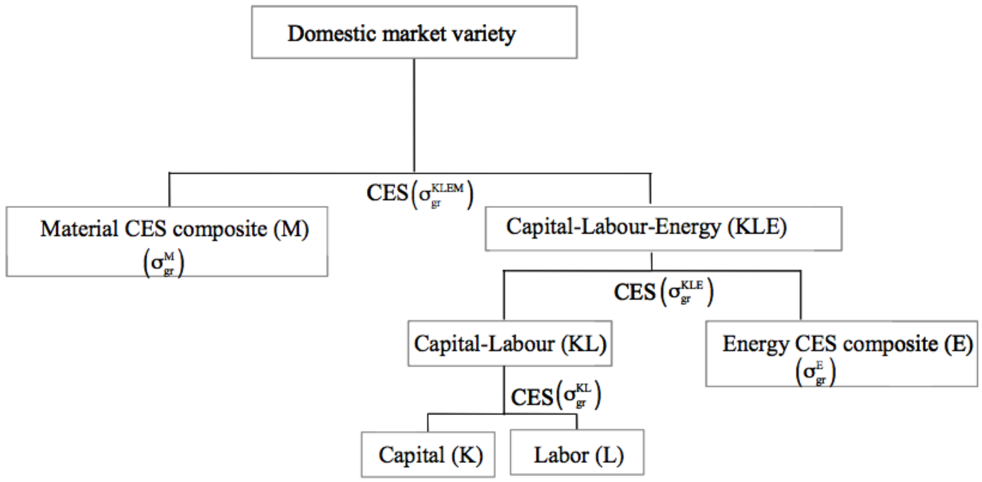

Figure 2: Nesting in Non-Fossil-Fuel Production

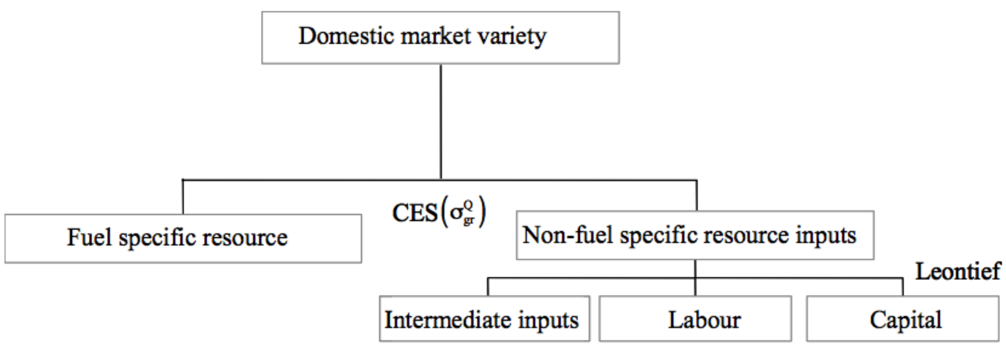

Figure 3: Nesting in Fossil-Fuel Production

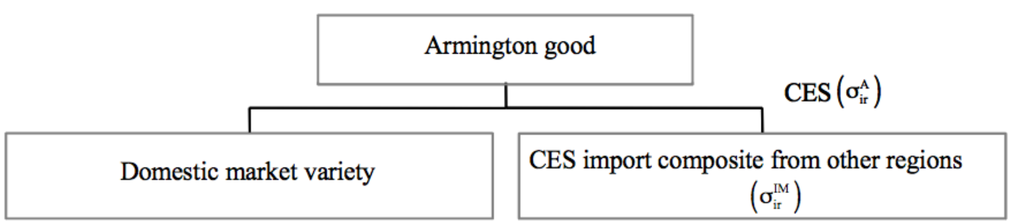

Figure 4: Nesting in Armington Composite Production

B Region and Sector Mappings

United States	United States
EU-27 plus European Free Trade Area	France, Germany, Italy, United Kingdom, Austria, Belgium, Denmark, Finland, Greece, Ireland, Luxembourg, Netherlands, Portugal, Spain, Sweden, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria, Cyprus, Switzerland, Norway, Rest of EFTA
Other Annex I minus Russia	Canada, Japan, Belarus, Ukraine, Australia, New Zealand, Turkey
China and Hong Kong	China, Hong Kong
India	India
Russian Federation	Russian Federation
Other Energy-Exporting Countries	Indonesia, Rest of North Africa, Nigeria, Rest of South Central Africa, Ecuador, Venezuela, Islamic Republic of Iran, Rest of Western Asia, Egypt, Bolivia, Malaysia
Other Middle-Income Countries	Albania, Armenia, Argentina, Azerbaijan, Bulgaria, Brazil, Botswana, Chile, Columbia, Costa Rica, Georgia, Guatemala, Kazakhstan, Sri Lanka, Morocco, Mauritius, Mexico, Panama, Peru, Philippines, Paraguay, Thailand, Tunisia, Uruguay, South Africa, Rest of Oceania, Rest of South America, Caribbean, Rest of North Africa, Rest of South African Customs Union
Other Low-Income Countries	Banglandesh, Ethiopia, Kyrgyzstan, Cambodia, Rest of East Asia, Lao People's Democratic Republic, Madagascar, Myanmar, Malawi, Mozambique, Nicaragua, Pakistan, Senegal, Tanzania, Uganda, Vietnam, Zambia, Zimbabwe, Rest of South Asia, Rest of Southeast Asia, Rest of Eastern Europe, Rest of Former Soviet Union, Rest of Western Africa, West of Central Africa, Rest of South Central Africa, Rest of Eastern Africa

Table 17: Mapping of Regions from the GTAP 8 Dataset

Coal	Coal
Crude Oil	Crude Oil
Natural Gas	Natural Gas
Refined Petroleum and Coal	Refined Petroleum and Coal
Electricity	Electricity
Chemical, Rubber, Plastic Products	Chemical, Rubber, Plastic Products
Iron and Steel	Iron and steel
Non-Ferrous Metals	Non-Ferrous Metal
Non-Metallic Minerals	Non-Metallic Mineral, Other Minerals
Water Transport	Water Transport
Air Transport	Air Transport
Other Transport	Other Transport
All Other Goods	All Other Goods

Table 18: Mapping of Sectors from GTAP 8 Dataset

Physical Capital	Physical Capital
Labor	Unskilled Labor, Skilled Labor
Natural Resources	Natural Resources

Table 19: Mapping of Factors from GTAP 8 Dataset