Climate Clubs:
Designing a Mechanism to Overcome Free-riding in International Climate Policy[1] [2]

William Nordhaus

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Abstract

Scientists and economists have developed an extensive understanding of the science, technologies, and policy instruments involved in climate change and slowing emissions. However, it has proven difficult to overcome the obstacles to reaching international agreements caused by free-riding, as seen with the defunct Kyoto Protocol. This study examines the club as a model for international climate policy. It asks whether there any stable climate treaties (coalitions of countries) that can improve significantly on the non-cooperative equilibrium. The analysis considers treaties both with and without penalties or sanctions on non-participants.

The bottom line of this study is the following: Using a simplified representation of climate change economics and international trade, it finds that without sanctions there is no stable climate coalition other than the non-cooperative minimal-abatement coalition. However, a regime with small trade penalties on non-participants can induce a stable coalition with globally efficient levels of abatement. Moreover, such a regime would attract a large majority of countries relative to the current situation, where international climate treaties are essentially voluntary. The essential feature for making the club effective is uniform penalty tariffs on non-participants.

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[1] The author is Sterling Professor of Economics at Yale University. Email: william.nordhaus @yale.edu.

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I. Bargaining and climate coalitions

A. Free-riding and the Westphalian system

Subject to many deep uncertainties, scientists and economists have developed an extensive understanding of the science, technologies, and policies involved in climate change and slowing emissions. Much analysis of the impact of national policies such as cap-and-trade or carbon taxes, along with regulatory options, has been undertaken.

Notwithstanding this progress, it has up to now proven difficult to construct programs to induce countries to join in an international agreement with significant reductions in emissions. The fundamental reason is that there are strong incentives for free-riding in current international climate agreements. *Free-riding* occurs when a party receives the benefits of a public good without contributing to the costs of producing the benefits. In the case of the international climate-change policy, countries have an incentive to rely on the emissions reductions of others without taking commensurate domestic abatement activities. To this is added temporal free riding when the present generation benefits from enjoying the consumption benefits of high carbon emissions, while future generations pay for those emissions in lower consumption or a degraded environment. The result of free-riding is the failure of the only significant international climate treaty, the Kyoto Protocol, and the difficulties of forging effective follow-up regimes.

While free-riding is pervasive, it is particularly difficult to overcome for global public goods. Global public goods differ from national market failures because there are no mechanisms – either market or governmental – to deal with them effectively. Arrangements to secure an international climate treaty are hampered by the Westphalian dilemma. The 1648 Treaty of Westphalia in 1648 established the central principles of modern international law. First, nations are sovereign and have the fundamental right of political self-determination; second, states are legally equal; and third, the system recognized the principle of non-intervention by states in the internal affairs of other states. The Westphalian system as implemented requires that countries consent to joining international agreements, and all agreements are essentially voluntary (Treaty of Vienna, article 34).

B. Clubs as a mechanism to overcome free-riding

Over the centuries, nations have overcome many transnational conflicts and spillovers through international agreements. There are over 200,000 U.N. registered treaties and actions which are presumptive attempts to improve the participants' welfare. Countries enter into agreements because joint action can take into account the spillover effects among the participants.

How have countries overcome the tendency toward free-riding associated with the Westphalian system? Consider the many important international agreements in international trade and finance as well as alliances that have reduced the lethality of interstate military conflicts. This is often accomplished through the mechanism of "clubs." A club is a voluntary group deriving mutual benefit from sharing the costs of producing an activity that has public-good characteristics. The gains from a successful club are sufficiently large that members will pay dues and adhere to club rules in order to gain the benefits of membership.

The theory of clubs is a little-known but important corner of the social sciences. (For an early essay, see Buchanan, 1965, while for a fine survey, see Sandler and Tschirhart, 1980.) The major conditions for a successful club include the following: (1) that there is a public-good-type resource that can be shared (whether the benefits from a military alliance or the enjoyment of a golf course); (2) that the cooperative arrangement is beneficial for each of the members; (3) that non-members can be excluded or penalized at relatively low cost to members; and (4) that the membership is stable in the sense that no one wants to leave. For the international-trade regime, the advantages are the access to other countries' markets with low trade barriers. For military alliances, the benefits are peace and survival. If we look at successful international clubs, we might see the seeds of an effective international system to deal with climate change.

The organization of this paper is as follows: After a sketch of the proposal, I begin with a discussion of the issues of free-riding and previous analyses of potential solutions. I examine potential approaches to internalizing the transnational spillovers and conclude that a climate club with penalties for non-members is the most useful mechanism. The following sections develop a model of trade and climate change (the TRICE model) and show the results of illustrative calculations. The bottom line – that clubs with penalties or sanctions on non-participants can support a strong international climate agreement – is summarized at the end of the paper.

C. A sketch of the Climate Club

The idea of a Climate Club should be viewed as an idealized solution of the free-riding problem that prevents the efficient provision of global public goods. Like free trade or physics in a vacuum, it will never exist in its pure form. Rather, it is a blueprint that can be used to understand the basic forces at work and sketch an actual structure.

Here is a brief description of the proposed Climate Club: The club is an agreement by participating countries to undertake harmonized emissions reductions. The agreement envisioned here centers on an "international target carbon price" that is the focal provision of an international agreement. For example, countries might agree that treaty requires a minimum domestic carbon price of $25 per ton of CO_2 and the equivalent for other covered greenhouse gases. Countries could meet the international target price requirement using whatever mechanism they choose – carbon tax, cap-and-trade, or a hybrid.

A key part of the club mechanism (and the major difference from all current proposals) is that non-participants are penalized. The penalty analyzed here is uniform ad valorem tariffs on the imports of non-participants into the club region. Calculations suggest that a relatively low tariff rate will induce participation as long as the international target carbon price is not too high.

An important aspect of the club is that it creates a strategic situation in which countries acting in their self-interest will choose to enter the club and undertake high levels of emissions reductions because of the structure of the incentives. The balance of this study examines the club structure more carefully and provides an empirical model to calculate its effectiveness.

II. Background on International Agreements on Climate Change

A. Basic free-riding equilibrium

There is a large literature on the strategic aspects of international environmental agreements, including those focused on climate change. One important strand is the analytical work on global public goods. The clear message is that without special features the outcome will be a prisoners' dilemma or tragedy of the commons in which there is too little abatement. We can illustrate this point with a simple model that will form the backbone of the empirical model below.

I begin by analyzing the costs and benefits of national climate policies in a non-cooperative (NC) framework (Nash 1950). In the NC framework, countries act individually and are neither rewarded nor penalized by other countries for not participating in a climate regime. Non-cooperative behavior implies that countries take abatement actions only to the extent that they themselves benefit, and the impacts on the rest of the world are largely ignored in the national calculus. The analysis assumes that countries maximize their national economic welfare and ignores partisan, ideological, myopic, and other non-optimizing behaviors. While history is full of woodenheaded actions of countries and their leaders, attempting to incorporate these features is beyond the scope of this study of climate regimes.

Non-cooperative equilibrium in a one-shot decision

Begin by assuming that countries choose their policies once and for all in a single decision. I take a highly stylized structure, but the most complex models extant have virtually identical results.

For this example, I assume that the emissions-intensities (σ) and the damage-output ratios are identical for all countries and that counties only differ in their sizes. In what follows, W = total economic welfare, A = abatement cost, D = damages, Q = output, E = actual emissions, $\bar{E}$ = uncontrolled emissions, and μ = emissions control rate $= (\bar{E} - E) / \bar{E}]$. The global social cost of carbon is denoted by γ, while θ is the country share of world output and other variables. This first analysis excludes trade.

The basic identity for country is that welfare equals output minus abatement cost minus damages. Abatement costs are assumed to be quadratic in the emissions reduction rate, $A_i = \alpha \mu_i^2 Q_i = \alpha \mu_i^2 \theta_i Q_w$, where α is the identical abatement-cost parameter and Q_w is world output. Damages are proportional to global emissions. All these imply for region *i:*

$$(1) \qquad W_i = Q_i - A_i - D_i = \theta_i Q_w - \alpha \mu_i^2 \theta_i Q_w - \gamma \theta_i (E_i + \sum_{j \neq i} E_j)$$

The potential for free-riding arises because most of the damages occur outside the emitting country. If we look at the last term in (1), we can define $\gamma \theta_i \sum_{j \neq i} E_j$ as the "external social cost of carbon" (SCC) for country *i.* This equals the marginal damages falling outside the emitting country. Note that in practice, the external SCC is very close to the global SCC.

Maximizing each country's welfare in a one-shot game, assuming no cooperation or strategic interactions, yields (as shown in the appendix) the non-cooperative emissions-control rate and domestic carbon price (τ_i^{NC}):

$$\mu_i^{NC} = \theta_i[\gamma\sigma/2\alpha] \tag{2}$$

$$\tau_i^{NC} = \theta_i\gamma \tag{3}$$

The most intuitive result shown in (3) is that a country's non-cooperative carbon price is equal to the country share of output times the global social cost of carbon. A less intuitive result is that a country's non-cooperative control rate (μ_i^{NC}) is proportional to the country share of world output, to the global SCC, to the emissions-output ratio, and inverse to the abatement-cost parameter. Equation (3) survives alternative specifications of the abatement-cost function, while (2) is sensitive to parameters such as the exponent in the cost function.

Under the simplified assumptions, we can also calculate the global average control rate and carbon price:

$$\bar{\mu}^{NC} = \sum_i \theta_i \mu_i = \sum_i \theta_i^2[\gamma\sigma/2\alpha] = (\gamma\sigma/2\alpha)H(\theta) \tag{4}$$

$$\bar{\tau}^{NC} = \sum_i \theta_i \tau_i = \sum_i \gamma\theta_i^2 = \gamma H(\theta) \tag{5}$$

In these equations, $H(\theta) = \sum_i \theta_i^2$ is the Herfindahl index of country size.

Equations (4) and (5) show the basic free-riding equilibrium for a global public good with the simplified structure. The globally averaged non-cooperative carbon price and control rate are equal to the Herfindahl index times the cooperative values. For example, if there are 10 equally sized countries, the Herfindahl index is 10%, and the global carbon tax and emissions-control rates are 10% of the efficient levels.

The Herfindahl index for country GDPs is about 12%, indicating that (when emissions-intensities and damage ratios are equal for each country) the non-cooperative control rate and carbon price are about 12% of the cooperative values. This figure is close to calculations that have been made in more complete models (see Nordhaus and Yang 1996, Nordhaus 2010, Bosetti et al. 2012). For example in the detailed RICE-2010 model with 12 regions, the non-cooperative price is estimated to be is 11% of the efficient price (Nordhaus 2010, supplemental materials).

Outcomes with repeated decisions

A more complete treatment of country interactions in climate-change policy views country interactions as a repeated game. The standard analysis uses the framework of a repeated prisoners' dilemma (RPD) game. For simplicity, assume that the structure above is repeated every few years with identical parameters. One equilibrium of a RPD is just the repeated inefficient NC equilibrium with minimal abatement as described above, However, because players can reward and punish other players for good and bad behavior, RPD games generally have multiple equilibria, including more efficient outcomes, if country discount rates are low (these being the generalized results of various folk theorems). However, cooperative outcomes are usually analyzed in the context of coalitions of countries, which is taken up in the next section.

The strategic significance of the analysis of NC behavior is threefold: First, the overall level of abatement in the non-cooperative equilibrium will be much lower than in the efficient (cooperative) strategy. A second and less evident point is that countries will have strong incentives to free-ride by not participating in strong climate-change agreements. Finally, the difficulty of escaping from a low-level, non-cooperative equilibrium is amplified by yet another factor – the intertemporal trade-off – because the current generation pays for the abatement while future generations are the beneficiaries of lower damages. But to a first approximation, the analysis in this section represents the world as of 2015.

III. Climate Coalitions and International Environmental Treaties

A. Optimal coalitions without external penalties: bottom-up v top-down coalitions

Might coalitions of countries form cooperative arrangements or treaties that improve on non-cooperative arrangements? Questions involving the formation, value, and stability of coalitions have a long history in game theory, oligopoly theory, as well as in environmental economics. In this section, we analyze coalitions without external penalties, that is, ones that have self-contained payoffs and cannot be enforced by third parties or linked to other arrangements. The importance of external penalties is explored in the next section.

In the context of climate change, coalitions of countries can form treaties that potentially improve the welfare of their members by taking concerted action. If several countries maximize their joint welfare, the optimized level of abatement will rise relative to the non-cooperative equilibrium because more countries will benefit. In the simple example described above, the coalition's optimal control rate shown in equation (2) will equal the global optimal times the coalition's share of world output. As the coalition increases to encompass all countries, the global level of abatement will tend toward the efficient rate. This result might form the basis for hopes that arrangements like the Kyoto Protocol will lead to deep emissions reductions.

Before turning to the analysis of coalitions, it will be useful to distinguish between "bottom-up" and "top-down" coalitions. The standard approach, reviewed in the next section, focuses on a bottom-up approach in which coalitions optimize their own self-interest and evolve into larger or smaller coalitions. Regional trade agreements are examples of this approach.

The Climate Club approach is instead a top-down approach. Here, the regime is optimized to attract large numbers of participants and attain high levels of abatement, and then countries decide whether or not to join. The Bretton Woods institutions such as the International Monetary Fund or the World Trade Organization are examples of this model.

B. Bottom-up coalitions and the small coalition paradox

Theoretical and empirical studies indicate that bottom-up coalitions for cartels and global public goods tend to be fragile and unstable. Work on coalition stability by Hart and Kurz (1983) found that coalitions are not generally stable, and their structure will depend upon the structure of the payoffs and the stability concept. Studies of the structure of cartels in oligopoly theory (see D'Aspremont, Jacquemin, Gabszewicz and Weymark, 1983, and Donsimoni, Economides and Polemarchakis, 1986) found that cartels are likely to be small, unstable, or of vanishingly small importance as the number of firms grows.

Studies in environmental economics and climate change find virtually universally that coalitions tend to be either small or shallow, a result I will call the "small coalition paradox." The paradigm for understanding the small coalition paradox is well discussed in Barrett's book on international environmental agreements (2003). His analysis emphases credible or "self-enforcing" treaties (Barrett 1994). These are ones that combine individual rationality (for each player individually) and collective rationality (for all players together). This concept is weaker than the concept of coalition stability discussed later, which adds rationality for each subset of the players. Barrett emphasizes the difficulties of reaching agreements on global public goods with large numbers of participants because of free-riding. Similar to the results for cartels, Barrett and others find that stable climate coalitions tend to have few members; therefore, as the number of countries rises, the fraction of global emissions covered by the agreement declines. He further argues, based on a comprehensive review of existing treaties, that there are essentially no treaties for global public goods that succeed in inducing countries to increase their investments significantly beyond the non-cooperative levels.

How can we understand the small coalition paradox? Here is the intuition for climate change: Clearly, two countries can improve their welfare by combining and raising their carbon price to the level that equals the sum of their SCCs. Either country is worse off by dropping out. It might be thought that, by increasing the number of countries in the treaty, this process would accumulate into a grand coalition that includes all countries. That conclusion is generally wrong. The problem arises because as more countries join, the cooperative carbon price becomes ever higher, and ever further from the NC price. The discrepancy gives incentives for individual countries to defect. When a country defects from an agreement with *m* countries, the remainder coalition (of *m-1* countries) would reoptimize its levels of abatement, while the defector free-rides on the abatement of remainder coalition. The exact size of the coalitions would depend upon the cost and damage structure as well as the number of countries.

The appendix provides a simple analysis of the stable equilibrium for identical countries with the cost and damage structure shown in equations (1) through (5). The only stable coalitions have two or three countries. (For simplicity, assume the lower number holds in the case of ties.) The number is independent of the number of countries, the social cost of carbon, output, emissions, and the emissions intensity. If there are 10 identical countries, there will be 5 coalitions of 2 countries each. The global average carbon price is twice that of the NC equilibrium. This result is clear because each country-pair has a carbon price that is the sum of the two countries' SCCs. The globally averaged carbon price will be one-fifth of the efficient level. With countries of different sizes but equal intensities, countries will group together in stable coalitions of size 2, with the countries of similar sizes grouped together in pairs (i.e., largest with second-largest, and so on).

The key result is that bottom-up coalitions perform only slightly better than the non-cooperative equilibrium.

C. Modeling Results for Bottom-Up Coalitions

The coalition theories described above generally use highly stylized structures and assumptions, so it is useful to examine empirical models of climate-policy coalitions with more realistic assumptions. Several empirical studies have examined the structure of coalitions or international agreements using a variety of alternative cooperative structures and coalition assumptions. A brief description of key studies is contained in the appendix.

The central results of existing studies reproduce the finding of the small coalition paradox. Without penalties on non-participants, stable coalitions tend to be small and have emissions reductions that are close to the non-cooperative level. In addition, many studies find that coalitions tend to be unstable, particularly if transfers are included.

IV. Sanctions on Non-Participants to Promote an Effective Climate Club

As noted above, the syndrome of free-riding along with the international norm of voluntary participation appears to doom international environmental agreements like the Kyoto Protocol. The suggestion in this paper is that a club structure – where sanctions are imposed on non-members – will be necessary to induce effective agreements. I analyze in depth a specific model of sanctions (tariffs on non-participants), but the model illustrates the more general point that sanctions are necessary to promote participation in agreements to provide global public goods.

A. Stable Coalitions

While it is easy to design potential international climate agreements, the reality is that it is difficult to construct ones that are *effective and stable.* Effective means abatement approaching the global optimum. The concept of stability used here is denoted as a *"coalition Nash equilibrium."* Under this definition, a coalition is stable if no group (sub-coalition) among the countries can improve its welfare by changing its status. That is, it combines individual rationality (for each player individually), collective rationality (for all players together), and coalition rational (for each subset of the players.) This is a natural extension of a Nash equilibrium, which applies to single countries. The concept is widely used in different fields and was originally called strong equilibrium in Aumann (1959); also see Bernheim, Peleg, and Whinston (1987). The term coalition Nash is more intuitive and is used here.

The small coalition paradox motivates the current approach. The goal here is to find a structure that is stable and effective for a wide variety of country preferences, technologies, and strategies. The most appealing structure is one that does not depend on sophisticated repeated-game strategies and instead has an efficient equilibrium for every period in a repeated game (or in the stage games). We therefore focus on one-shot games that have efficient and unique equilibria. If these are then turned into a repeated game, each of the one-shot games will be a sub-game perfect coalition Nash equilibrium, and the repeated game will have an efficient coalition-Nash equilibrium.

B. Transfers undermine coalition stability

The present study assumes that there is no sharing of the gains from cooperation among members of the coalition. In some cases, particularly those with asymmetric regions, allowing transfers may allow a more efficient treaty (see Barrett 2003, Chapter 13). However, allowing transfers also increases the dimensionality of the strategy space and may increase the potential for coalition instability.

Before discussing the strategic issues, a practical exception must be made for poor countries. We can hardly expect low-income countries struggling to provide clean water or engaged in civil conflict to make the same commitment as rich countries. So there might be a threshold for participation in terms of per capita income. But once countries graduate into the middle-income region, they would assume the obligations of club membership.

What happens if surplus-sharing is included as part of country strategies? If there are no sharing constraints, then coalition instability is inevitable in what might be called the stab-in-the-back syndrome. This can be seen in the case of three regions. Suppose that a cooperative agreement of the three regions has a surplus of 300 units, and agreements require a majority of countries. A first agreement might be to divide the surplus equally among the three regions as proposal A = (100, 100, 100). However, a coalition of the first two countries could propose another allocation as proposal B = (110, 110, 80), which would lead the first two countries to defect from proposal A to B. A little reflection will show that there is no stable coalition if the surplus can be divided arbitrarily. (For examples of how different sharing and voting rules lead to instability, see Roger Meyerson 1991, Chapter 9.)

One difficulty with use of differentiated emissions targets in the Kyoto Protocol was its stab-in-the-back instability. The initial allocation of permits across countries is a zero-sum distribution. It can generate the same instability as the example of the negotiation over side payments. One of the attractive features of a regime that focuses on carbon prices is that it can operate as a single-dimensional choice and thereby avoid stab-in-the-back instability.[3] A study of climate regimes by Weikard, Finus, and Altamirano-Cabrera (2006) confirms the potential for instability in climate agreements with transfers (see the appendix).

C. Introducing sanctions on non-participants

Both theory and history suggest that some form of sanctions on non-participants is required to induce countries to participate in agreements with high levels of GHG abatement. It will be useful to define "sanctions" or "penalties" carefully. In their landmark study of sanctions, Hufbauer, Schott, and Eliot (1990) define sanctions as governmental withdrawal, or threat of withdrawal, of customary trade or financial relationships. A key aspect of the sanctions analyzed here is that they benefit senders and harm receivers. This pattern contrasts with most cases analyzed by Hufbauer et al., whose studies show that sanctions usually impose costs on senders as well as receivers and thereby raise issues of incentive-compatibility.

The major potential instrument is sanctions on international trade. Whether and how to use international trade in connection with a climate treaty involves many issues – economic, environmental, international and domestic law, and diplomatic. I will emphasize the economic and strategic aspects and leave other aspects to specialists in those areas.

Two approaches to trade sanctions might be considered. A first approach, called carbon duties, would put tariffs on imports of non-participants in relation to the carbon content of imports. A second approach, called uniform penalty tariffs,

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[3] This point has been emphasized in Weitzman (2014), who shows that a single carbon price provides a more robust negotiating device that a cap-and-trade regime with country-differentiated permit allocations. The point is made less formally in Nordhaus (2013), Chapter 21.

would apply uniform percentage tariffs to all imports from non-participating countries. I discuss each of these in turn.

The central question addressed in this analysis is whether a club design which incorporates penalty tariffs on non-participants can produce a stable equilibrium or coalition that significantly improves on the non-cooperative equilibrium.

D. *Carbon duties*

A first approach called carbon duties —commonly proposed among scholars who have advocated this mechanism — would put tariffs on goods imported from non-participants in relation to the goods' carbon content. (These are also known as countervailing duties, but I will use the more descriptive term here.) Under this plan, imports from non-participants into a country would be taxed at the border by an amount that would be equal to the domestic price of carbon (or perhaps by an agreed-upon international target carbon price) times the carbon content of the import. Alternatively, under a cap-and-trade regime, the requirement might be that importers purchase emissions allowances to cover the carbon content of the imports.

The technique of carbon duties is commonly used when countries violate their trade agreements, and is also included in several international environmental agreements (see Barrett 2003 for an extensive history). The purposes of carbon duties are to reduce leakage, to level the competitive playing field, and to reduce emissions. The goal of increasing participation – which is emphasized here – is usually not included on the list.

Studies of carbon duties indicate they are complicated to design, have limited coverage, and do little to induce participation. As an example, consider CO_2 emissions from U.S. coal-fired electricity generation, which are a major source of emissions. Since the U.S. exports less than 1 percent of its electricity generation, the effect of tariffs here would be tiny. Modeling studies confirm the intuition about the limited effect of the carbon-duties mechanism. For example, McKibbin and Wilcoxen (2009) study the effects of carbon duties for the US and the EU. They find that the proposal would be complex to implement and would have little effect on emissions. Estimates of this approach using the TRICE model described below also indicate that it has limited effectiveness in promoting deep abatement (see the appendix).

E. *Uniform tariff mechanisms*

Given the complexity of carbon duties, I propose and analyze an alternative and simpler approach: a uniform percentage tariff. Under this approach, participating countries would levy a uniform percentage tariff (perhaps 2 percent) on all imports from non-participants. This mechanism has the advantage of simplicity and transparency, although it does not relate the tariff specifically to the carbon content of the import.

While the uniform tariff appears to be less targeted than carbon duties, it has a different purpose. It is primarily designed to increase participation, not to reduce leakage or improve competitiveness. The rationale is that non-participants are damaging other countries because of their total emissions of greenhouse gases, not only from those embodied in traded goods.

One objection to this approach is that a tariff on all imports is a major departure from the approaches authorized under national and international law. It would appear to collide with current treaties by raising tariffs above negotiated levels. It also departs from the principle of proportionality in having a binary "in or out" nature of the sanctions. However, this feature is central to having countries focus on two possible policies, and including proportional tariffs would lead to a different set of equilibria. While there may be ambiguities as to whether some esoteric exceptions can be used to justify the system of uniform, non-proportionate tariffs, trying to shoe-horn the proposed uniform-tariff mechanism into current law seems ill-advised.

For these reasons, an important aspect of the proposal will be a set of "climate amendments" to international-trade law, both internationally and domestically. The climate amendments would explicitly allow uniform tariffs on non-participants within the confines of a climate treaty; it would also prohibit retaliation against countries who invoke the mechanism. Requiring such amendments would emphasize that climate change is an especially grave threat, and that this approach should not be used for every worthy initiative.

F. Tariffs as internalization devices

We can interpret penalty tariffs as devices to internalize transnational externalities. Nations incur but a small fraction of the damages from climate change – less than 10% on average. Just as taxes or regulations are needed to correct externalities within nations, some analogous mechanism is needed for global public goods.

Tariffs on the trade of non-participants are a reasonable and realistic tool for internalizing the transnational externality. They have an important advantage that they are incentive-compatible sanctions. Many sanctions have the disadvantage that they penalize the penalyzer. For example, if Europe puts sanctions on Russian energy companies, this is likely to raise energy prices in Europe and hurt European countries. By comparison, the tariff mechanism analyzed here (a) imposes costs on the non-participating country but (b) benefits the country levying the tariff (by optimal-tariff reasoning). It also avoids the difficulty of the simple grim strategy or other similar punishments in n-person RPD games that they can only support a cooperative equilibrium for a few countries (as is discussed in the small coalition paradox). Because the penalty tariff penalty has the two features described above, it can support an efficient equilibrium for a large number of countries as long as the optimal-tariff effect operates.

How well-targeted are penalty tariffs? Using the TRICE model (which is described in the next section), I have examined the external effects of emissions of each region along with the regional impacts of the penalty tariff, and the results are shown in Figure 1.

Here are the calculations. I began with a \$25 per ton CO_2 global social cost of carbon. I then calculate each region's external SCC (defined above) by calculating the fraction of global damages that are experienced outside the country; in all cases, the external SCC is close to \$25 per ton CO_2. Multiplying the region's external SCC by the difference between the cooperative and non-cooperative emissions provides the externality, shown as the left bar in Figure 1. In this example, when the US decides not to participate, it increases its annual emissions by about 800 million tons, and this produces \$16 billion of additional external damages.

I then calculate the cost from the penalty tariff that a country incurs by not participating in the climate club. For these calculations, I used a 2% penalty tariff. The calculation labeled "Cost of out" shows the cost of leaving the club when all other countries are in. For example, the US has a welfare loss of \$10 billion when it does not participate and the penalty tariff is 2%. This cost is below the external damages of \$16 billion. For all regions, the sum of the transnational externalities is \$124 billion, while the sum of the costs of non-participation of all regions is \$98 billion. Additionally, the Figure shows the "benefit of in," which is the benefit of forming a club of 1, when the country is the only member of the club. For the US, the benefit of in is \$23 billion. Appendix Table B-7 shows the results for all regions.

The calculations provide a surprising result. They indicate that a penalty tariff provides incentives that are reasonably well targeted to the transnational externalities. The penalty always has the correct sign, and the size of the penalty is the right order of magnitude with a 2% tariff. However, because of different trade and emissions patterns, the externality and the trade penalty are imperfectly aligned. Note that the tariff effect changes with club size, so the internalization effect is variable. But on the whole, an appropriate tariff appears to be remarkably well-calibrated to the CO_2 externality.

G. Prices or quantities?

The Climate Club discussed here focuses on carbon prices rather than emissions reductions as the central organizing principle for an international agreement. While at an abstract level either approach can be used, a review of both theory and history suggests that use of prices is a more promising approach.

Quantitative targets in the form of tradable emissions limits have failed in the case of the Kyoto Protocol, have shown excessive price volatility, lose precious governmental revenues, and have not lived up to their promise of equalizing prices in different regions. Moreover, as emphasized by Weitzman (2014), prices serve as a simpler instrument for international negotiations because they have a single dimension, whereas emissions reductions have the dimensionality of the number of regions. To the extent that carbon-price targets lead to carbon taxes, the administrative aspects of taxes are much better understood around the world than marketable emissions allowances, and they are less prone to corruption. This discussion is clearly just a sketch, but it provides some of the reasons for preferring price over quantity targets as part of an international climate regime. (For an extended discussion of the relative merits of prices and quantities, see Nordhaus 2013.)

H. How to get started?

An important question is, how would a top-down Climate Club get started? Who would define the regime? Would it begin with a grand Bretton-Woods conference? Or would it evolve from a small number of leaders who see the logic, define a regime, and then invite the key countries to join?

There is no clear answer to these questions. International organizations evolve in unpredictable ways. Sometimes, it takes repeated failures before a successful model is developed. The histories of the gold and dollar standards, cholera conventions, the WTO, NATO, and the Internet all emphasize the unpredictability in the development of international regimes (for some histories, see Cooper 2001). The destination is clear, but there are many roads that will get there.

V. Modeling coalition formation: The TRICE model

A. *Description of the model and sources*

Economic analysis can describe the basic structure of a Climate Club. But detailed empirical modeling is necessary to determine the effectiveness of different regimes in the context of actual emissions, damages, climate change, and trade structures. For this purpose, I next describe a climate-economic model with trade sanctions called the TRICE model (Trade in the Regional Integrated model of Climate and the Economy). It is a static version of the multi-regional RICE model (Nordhaus 2010) with the addition of a trade module. For those familiar with economic integrated assessment models (IAMs), the framework is a regional IAM with an international trade module that includes the impacts of tariffs on real national income.

The current version has 15 regions, including the largest countries and aggregates of the balance of the countries. The regions are the US, EU, China, India, Russian Federation, Japan, Canada, South Africa, Brazil, Mideast and North Africa, Eurasia, Latin America, tropical Africa, middle-income Asia, and the ROW (rest of the world). For this study, I will assume one period, but the period might extend for several years for which the treaty is in effect. The model includes exogenous output, baseline CO_2 emissions, and a baseline trade matrix for the 15 regions. Countries produce a single composite commodity, and CO_2 emissions are a negative externality of production. Regions can reduce emissions by undertaking costly abatement.

The marginal damages of emissions (social cost of carbon or SCC) are assumed to be constant. This is reasonably accurate for small time periods because emissions are a flow, damages are a function of the stock, and the flow-stock ratio is small. The fact that the SCC is little affected by abatement levels is shown in Nordhaus 2014, Table 1, where the near-term difference in SCC between the optimal and baseline policies is 5%.

The damages estimates are drawn from a recent comparison of estimates of the social cost of carbon (Nordhaus 2014). That study found a central estimate of the global SCC of $24 per ton CO_2 in 2011 US$ for the cost-benefit optimum for 2020 emissions. However, estimates from other studies range from \$10 to as high as \$100 per ton CO_2 for alternative goals and discount rates. I therefore use a range of \$12.5 to \$100 per ton CO_2 for the global SCC.

Estimates of national SCCs have proven difficult to determine because of sparse evidence outside high-income regions. Appendix Table B-1 shows the substantial differences in national SCCs in three integrated assessment models, the RICE, FUND, and PAGE models. Note that the conceptual basis of the national SCCs used here is the calculations made by nations – using their national values, analyses, and discount rates. They are likely to differ from estimates of modelers using uniform methods and low discount rates. For the central estimates, it is assumed that national SCCs are proportional to national GDPs. This assumption is primarily for simplicity and transparency but also because the national estimates are so poorly determined. However, sensitivity analyses discussed below and in the appendix indicate that alternative estimates lead to identical results on participation.

The abatement costs combine global estimates from the DICE model detailed regional estimates from an engineering model by McKinsey Company. Abatement costs are largely determined by the carbon-intensity of a region, which are relatively reliable data. Aside from carbon-intensity, the differences among regions are largely technological and sectoral as analyzed by McKinsey's study.

The major new feature is to include the effects of international trade and tariffs on the economic welfare of each region. For both computational and empirical reasons, the model develops a reduced-form trade-benefit function. The model includes estimates of the impact of changes in the average tariff rate of each country on each other country. As an example, the model estimates that if the US imposes a uniform additional tariff of 1% on Chinese imports, US net national income rises by 0.010% and China's net national income falls by 0.018%.

Estimates from the optimal-tariff literature indicate that countries have net benefits if they impose small uniform tariffs on other countries. Similarly, all countries suffer economic losses if they are the targets of tariffs levied by other countries. I assume that the tariff function is quadratic with a maximum at the optimal tariff rates. The numerical parameters of the reduced-form trade-benefit function are derived from a model developed and provided by Ralph Ossa (2014). Details are provided in the appendix.

Macroeconomic and emissions data are taken from standard sources. GDP and population are from the World Bank. CO_2 emissions are from the Carbon Dioxide Information Action Center (CDIAC 2014). Note that I include all industrial CO_2 emissions but exclude land-use emissions as well as non-CO_2 GHG emissions or other sources of climate change. The interregional trade data are based on data from the United Nations Conference on Trade and Development (UNCTAD 2014).

The model considers only one period, centered on 2011. It can be interpreted as a game with a single long period or as a repeated game with a constant payoff matrix. As discussed above, we are looking for an efficient solution to the stage game that will also be an equilibrium of the repeated game.

Countries are assumed to maximize their perceived national self-interests, and the welfare of the rest of the world is not counted in their interests. Their estimates may turn out to be right or wrong, but they are the basis of treaty negotiations. To avoid stab-in-the-back instability, I assume that there are no side payments among countries. Treaties are assumed to be stable in the sense of being coalition Nash equilibria, which means that they are stable to all alternative sub-coalitions.

B. Gains and losses from participation

The non-cooperative equilibrium is the starting point in international relations. Consider the decision of a single country whether to participate in a climate club. Recall that participation in the climate club requires countries to have a domestic carbon price at least as high as the minimum international target carbon price. The choice of climate policies is simple once that decision is made. A non-participant will choose the low NC carbon price because that maximizes national welfare for non-participants. Similarly, a participant will choose the international target carbon price to meet its obligations because the cooperative price is above the NC price. (In the unlikely case that the NC price is higher than the target price, the country would choose the NC price).

In considering whether or not to participate in the high cooperative abatement regime, countries face two sets of costs. The first cost is the additional abatement cost (net of reduced damages) of participation. The additional abatement costs are greater than the reduced damages. This fact shows immediately why countries will not voluntarily depart from the NC equilibrium without some further inducements to participate.

This leads to the second class of effects of participation – the gains and losses from participating in the climate club. The present study analyzes a uniform tariff on all goods and services imposed by participants on the imports from non-participants into the climate club. Figure 2 shows the basic structure of the tariff arrangements. As shown in the two cells on the left, the Club treaty authorizes tariffs on non-participants into the Club region, with no tariffs on intra-Club trade. The two cells on the right indicate that there are no tariffs, which assumes no reaction or retaliation of non-Club members to the Club.

VI. Algorithmic Issues

Finding the equilibrium coalition, as well as determining stability and uniqueness, is computationally demanding. Consider a global climate club game with *n* regions. The payoff functions for the regions are functions of the parameters of the game, including output, emissions, damages, the trade technology, and the tariff penalty function. In addition, the payoffs depend up the participation of each of the other players in a non-monotonic fashion, and participation rates are binary variables.

In the most general version, discussed above in the section on bottom-up coalitions, there may be multiple coalitions (i.e., regional groupings). This outcome is seen in trade associations and military alliances formed on the basis of costs, location, and ideologies. In the case of multiple coalitions, there will be on the order of *n!* possible coalitions. For our study, with 15 regions and multiple regimes, that would consist of about 10^{12} coalitions and would be computationally infeasible.

However, in the case of global climate change, it is more natural to consider a situation where there is only one Climate Club – where countries design and join a single global climate treaty. Assuming a single coalition has the computational advantage that it limits the number of potential coalitions to 2^n (or 32,768) coalitions, which can easily be calculated.

The problem is combinatorial in nature, and its solution is thought to be in the class of NP-hard problems (Wooldridge and Dunne, 2004).There appears to be no efficient algorithm for calculating stable coalitions (Rahwan 2007). In principle, we would need to take each of the 2^n coalitions and determine whether they are stable against all the other $2^n - 1$ coalitions, which requires about $2^{2n} \approx 10^9$ comparisons. While this is computationally feasible, it is unnecessarily burdensome, particularly for model construction and comparison of regimes.

I therefore settled on an evolutionary algorithm to find stable coalitions. This is similar to a genetic algorithm except that it considers mutations of all elements rather than just local searches. This proceeds in the following steps: (1) Start with an initial coalition (the null coalition, the grand coalition, or a random coalition) and calculate the outcomes and net benefits. Denote these the initial "base coalition" and "base outcomes." (2) Randomly generate a "change coalition" of a set of m regions from the n regions. Assume that each of the m regions changes its participation from out to in or from in to out. (3) Construct a new test pattern of participations substituting the new participation status of the change coalition. (4) Calculate the test net benefits of the new test participation for each region. (5) If the test net benefits are Pareto improving for the change coalition, substitute the test participation pattern and other outcomes for the prior base outcomes. Note that while the results of the test coalition will be Pareto improving for the change coalition in the new base outcomes, it may not improve the welfare for the balance of regions. (6) Go back and restart from #2 to generate a new random change coalition and then go through steps #3 to #5. (7) The procedure stops either when (a) the process cycles (a coalition structure repeats), or (b) no other coalition is able to overturn the existing coalition.

Note that the termination in 7(b) cannot be determined with certainty because of the probabilistic nature of the algorithm. However, because the change coalition is randomly selected, we can determine that in the worst case the likelihood of there being an overturning coalition that has not been found is no more than $(1-2^{-n})^m$ after m iterations. Experiments indicate that stable coalitions are usually found within 100 iterations. We test to 50,000 iterations and random starting coalitions to test stability. While this algorithm might potentially be improved with bounding refinements, the flexibility of the evolutionary algorithm for finding stable coalitions suggests it is adequate. Further details are provided in the appendix.

VII. Results

A. A first example

Before diving into the results, it will be useful to present a numerical example. Assume that the international target carbon price is $25 per ton; that the penalty tariff rate is 4%; that all high-income countries participate; and that the U.S. is considering whether to participate. The numbers are shown in Table 1.

All figures in this study apply to annual output and prices for 2011 in 2011$. The figures are often provided with two or three significant digits, but this is for presentational purposes and should be interpreted in the context of the uncertainties inherent in modeling as well as the results of the sensitivity analyses discussed below.

First consider a Kyoto-type regime, with no sanctions when countries do not participate, which is the first line in Table 1. If the U.S. does not participate, it expends $0.3 billion per year for abatement and has reduced damages (from all countries' abatement relative to zero abatement) of $7.3 billion per year. Net climate-related benefits are $7.0 billion per year. In the no-sanctions regime, if the U.S. participates and sets a domestic carbon price of $25 per ton, it expends $11.9 billion annually in abatement and has reduced damages of $10.7 billion per year, for net climate-related benefits of -$1.2 billion annually. So without sanctions, the best national strategy is not to participate, with an annual net advantage of $8.2 billion.

However, with a 4% penalty tariff on non-participants, the numbers change dramatically. Here, the U.S. has trade impacts of -$15.6 billion per year if it does not participate. This comes primarily from the terms of trade losses induced by tariffs on the U.S. imposed by participants. If the U.S. does participate, it has positive trade impacts of $36.7 billion per year because it levies tariffs on the remaining non-participants.

Taking the sum of climate-related gains and trade benefits with the 4% penalty tariff, the U.S. would have a positive impact of $35.5 billion per year as a participant. By contrast, the U.S. would have an annual impact of -$8.6 billion as a non-participant. The U.S. would have an incentive of a net gain $44.1 billion per year to join the agreement taking account only of its own national economic benefit. In this example, it is not even a close call on whether to participate.

The point of this simple example is to show that nations acting in their self-interest would join a high-income-country club with a 4% tariff but would not join such a club with a zero penalty tariff.

B. Basics of the simulations

The central analysis undertaken here examines 44 different regimes for the Climate Club. A *regime* in the following is defined as a combination of target carbon price and tariff rate. The regimes analyzed here involve 4 different international target carbon prices and 11 different tariff rates. The carbon prices are $12.5, $25,

\$50, and \$100 per ton of CO_2. While other values have been used in the literature, this spans the range of common targets, as discussed above. The tariff rates range from 0% (no penalty) to 10%. The upper end is chosen as one that would begin to place a serious burden on both the trade and the enforcement systems.

For each of the calculations, I started with a base set of participants and then used the evolutionary algorithm to find a stable coalition (if one exists), with multiple restarts and two different platforms to test stability. The results were sensible in all cases and will be discussed below. This paper presents the results primarily in graphical form. The numbers underlying the figures are contained in the appendix.

C. Results for participation

The first question is whether the penalty structure is sufficient to induce participation. In other words, how many of the 15 regions participate in the Climate Club? Figure 3 shows the number of participating regions for different tariff rates and different target carbon prices. The bars are arrayed from left to right by increasing tariff rates. (As a technical aside, there are six unstable regimes. Results for these are averages of quasi-stable coalitions within these six as explained below.)

The results are straightforward: No country joins the Climate Club without trade sanctions (i.e., at a zero tariff rate). This key result confirms theory and observation. For low target carbon prices, all or most countries join even for very low tariff rates. For target carbon prices of \$50 and \$100 per ton, high penalty tariffs are required to induce participation. With a \$100 per ton target, full participation is not attained even with the highest tested tariff rates. The participation rate rises monotonically with the penalty tariff rate.

D. Results for actual carbon prices and abatement

The next question is the success of different arrangements in inducing abatement. Figure 4 shows the level of the globally averaged carbon price for different regimes. The results here are similar to those for participation but in effect weight the results by region size.

For target carbon prices of \$12.5 and \$25, the treaty attains the goal of having the global carbon price equal the target price (which is equal to the global SCC) even at low tariff rates. For a $50 target carbon price, the target carbon price is almost reached with a 5% tariff.

For a carbon price target of $100, the regime achieves no gain over a regime with a target price of $50 until the highest tariff rate. Indeed, at medium tariff rates, we see a Laffer-curve result as the actual global carbon price is *lower* with the $100 per ton target than with the $50 per ton target. The reason is that abatement is so costly in the cooperative regime that most countries choose to accept the trade penalties. This then leads to a low participation rate and a low actual penalty on non-participants because so few countries are in the Club.

Results on emissions reduction rates are virtually identical to those of the carbon prices except for scaling. (???) The reason is that the model assumes that the emissions control rate is linear in the carbon price. Small differences from complete linearity arise because of aggregation over regions.

E. Economic gains from the Climate Club

What are the economic gains from the Climate Club? The Club is designed to increase economic welfare by overcoming free-riding. Figure 5 shows the net economic gains for different regimes, while Figure 6 shows the regime efficiency as measured by the percentage of the cooperative gains that are realized.

First examining Figure 5, it is clear that the gains to cooperation are substantial. Taking as an example the case of $50 per ton of CO_2, the income gain from non-cooperative actions is $63 billion per year. The most successful cooperation regimes have gains of $312 billion per year. (Again, all are scaled to 2011 output and prices.)

Figure 6 shows the extent to which different regimes succeed in achieving the potential gains from cooperation. At benchmark levels of $12.5 and $25 per ton, the regime captures all of the potential gains for tariff rates of 3% or more. Similarly, at the $50 per ton rate, the Club achieves virtually all the potential gains with tariff rates of 5% or more. However, for the highest target carbon price, the regime gets at most one-tenth of the potential gains except at the highest tariff rates.

F. Trade inefficiencies

How large are the trade costs relative to the climate gains? Note to begin with that there are no trade losses with full participation because there are no sanctions. However, with partial participation, there will be efficiency losses because of the tariffs. Consider a regime with a low tariff and a low target carbon price, for example, a 1% tariff and a $25 per ton target carbon price. Here, there are 6 non-participants. The gains from the regime are $34 billion while the trade inefficiencies are $0.4 billion. At the other extreme, consider a $50 target price with a tariff of 6%. For this regime, there are only two non-participants. The gains from the club are $228 billion, while the trade inefficiencies are $0.7 billion. In all except the most extreme cases, the gains from cooperation far outweigh the trade losses.

G. To Join or Not to Join?

An interesting question is to determine which countries join and which stay out of the Climate Club. On first principles, the joiners are those with low abatement costs, low carbon-intensity, high damages, and high trade shares.

Table 2 shows the percentage of the cases where a specific region participates. This examines the fraction of the 4 x 10 international target carbon prices and positive tariff rates.

A related question is, who gains and who loses from the Climate Club? The answer depends upon the regime that is chosen. Figure 7 shows the net gains and losses for four different sets of parameters. All major regions gain from the club relative to the non-cooperative outcome. In the entire set of 40 regimes and 15 regions, there are 69 (12%) cases where countries lose relative to the non-cooperative regime.

What explains the pattern of gains and losses? It is primarily determined by the carbon-intensity of production and trade openness. South Africa and Eurasia are the only countries showing a high fraction of losses because they have high carbon intensity. They must either incur expensive abatement costs or pay dearly through sanctions on their international trade. Countries with high damages (such as India) show gains in all regimes.

H. The Kyoto Protocol as a Failed Regime

One test of the approach used here is to examine the stability of the Kyoto Protocol. This agreement included at the outset a substantial fraction of global emissions and would, if it had broadened and deepened, have made a substantial contribution to slowing the growth of emissions. However, it failed to gain new adherents, and some of the members with binding commitments, particularly the U.S., dropped out.

Conceptually, the Kyoto Protocol was a climate club with no sanctions. To test its coalition stability, I formed an initial club with the only original Annex I Kyoto Protocol countries having binding emissions commitments with no penalties for non-compliance (0% tariff). Starting with the original Kyoto coalition status, I tested for coalition stability as described above.

All of the simulations collapsed to the non-cooperative equilibrium. (See Figure B-5 in the appendix for the simulations.) This might not be surprising in light of the analysis above. However, recall that the analytical models assume much more environmental and economic homogeneity than is seen in reality. Perhaps some strange combination of damages, abatement costs, and carbon intensities might lead to limited cooperation. However, for the modeling structure used here, the Kyoto Protocol could not survive.

So the conclusion from this simple exercise is that the Kyoto Protocol coalition structure was doomed from the start. It did not contain sufficient glue to hold a cooperative coalition together.

I. A Broader Perspective on Treaty Formation

The present analysis focuses on the design of a Climate Club and the extent to which different club designs succeed in inducing efficient participation and abatement. In reality, treaties do not spring full-grown but emerge from a complicated process. The key steps are negotiation, ratification, implementation, and re-negotiation (see Barrett 2003, Chapter 6).

The present study focuses on negotiation and assumes that once treaties are negotiated, they are ratified and implemented (so there are no "cheap talk" negotiations). Negotiations take place in two parts. The first stage is treaty design, while the second is the decision whether to participate. For the Kyoto Protocol, the U.S. was deeply involved in treaty design, but (after a complex domestic political struggle) chose not to participate. The last section explains the U.S. non-participation and the eventual demise of the Kyoto Protocol as the failure to design a treaty that would lead to widespread participation and renewal.

Turn briefly to the issue of treaty design. Suppose that climate negotiations consider the different climate club regimes analyzed above. Depending upon the rules of the negotiations, which of the possible regimes would be chosen to be signed, ratified, and implemented?

We consider these questions for a single case where the global SCC is $25 per ton CO_2 and where countries assume that all countries participate. Individual countries have their own SCCs (say that the U.S. SCC is $4 and India's is $2), as well as their national abatement cost functions. If countries are just scaled-up or –down replicas, then all would prefer a $25 per ton target price. If countries differ, their targets will differ. For example, countries with high damages will prefer a high target carbon price because they will benefit from higher global abatement; countries with high abatement costs will prefer a low target carbon price because a low target price reduces their abatement costs. The analog for athletic clubs is that people who desire minimal facilities want low dues, while those who prefer extensive coverage vote for higher dues.

How does the desired international target carbon price vary across regions? Figure 8 and Table 3 show the distribution of preferred target carbon prices for regions where the global SCC is $25. The curves show on the vertical axis the fraction of regions that would prefer an international target carbon price at least as high as the reference price on the horizontal axis. The non-cooperative regime is shown at the upper left with the circle marked "NC." The curve marked "preferred" shows the distribution of regional preferred rates (the distribution of first choices). The line marked "breakeven" shows the distribution of prices at which the country would be indifferent between the target price and a zero price. The breakeven is close to twice the preferred.

The median preferred international target carbon price using GDP weights is $28 per ton, which is slightly above the global SCC. The median breakeven carbon price is $56 per ton. Additionally, all countries prefer a weak regime to the non-cooperative regime. Even the least enthusiastic region (South Africa) would prefer a target price of $17 per ton to the NC equilibrium. Finally, not shown, is that that the preferred and breakeven prices for each region are proportional to the global SCC. If the global SCC doubles, and the distribution of SCC across regions stays the same, then the preferred target carbon price will also double.

J. Unstable regimes

Of the 44 regimes, six displayed coalitional instability, and these can be easily understood. For example, three came with a $50 international target carbon price and low tariff rates. For example, with a tariff rate of 2%, the solution cycled around among a small number of quasi-stable coalitions with an average of 2.9 participants. The other instabilities came with the $100 per ton target price and high tariff rates.

For example, with $100 per ton target price and a penalty tariff of 9%, the coalitions cycled with an average of 3.9 regions.

The instabilities arise because the gains from participation are close to equal in these different mid-sized coalitions. Hence, the solution cycles among quasi-stable coalitions as each outbids the others. None of the regimes degenerates to the non-cooperative equilibrium. Rather, they cycle among similar numbers of participants and levels of abatement.

Another potential source of instability would arise if the damage function has a catastrophic threshold (which has not been modeled in the TRICE model framework). In the limit, assume that if emissions pass some quantity (below the emissions in the NC equilibrium), then damages for each region are unlimited. There will be multiple combinations of abatement by different regions that can stay under the catastrophic threshold. It might be stable to a single country leaving, but would not be stable to multiple countries entering and leaving. This example suggests that highly non-linear damages open up a different set of issues for regime design.

K. Sensitivity analysis

How sensitive are the results to alternative parameters? The sensitivity analyses are presented in detail in the appendix, and the results are summarized here. I examine the impact of three different sets of parameters. The first is alternative estimates of the regional distribution of the global SCC. There are virtually no impacts of this sensitivity test on the participation rate or on the global carbon tax for any of the regimes. The second sensitivity test is for the parameter of the abatement-cost function, which is varied by a factor of three. The results showed considerable sensitivity, especially for global SCC of $50 and $100. The optimal tariff was varied over a range of a factor of 6. This had virtually no impact on the outcomes. The main variable that affects the outcome is the global social cost of carbon, as shown in the figures and tables.

Those familiar with the literature on climate-change economics will wonder what happened to the discount rate, which is critical in virtually all areas. The answer is that the discount rate will primarily affect the global and national SCCs, but has little effect on the outcomes *conditional on the SCCs*. For example, a lower discount rate will raise the estimated global SCC, perhaps from $12.5 to $25. This will lead to a higher target carbon price, higher emissions reductions, and lower annual damages. There will be second-order effects through cost-of-capital factors, GDP, and other economic variables. But a changed discount rate with affect the outcome primarily through changes in the SCC.

V. Conclusions

The present study analyzes the syndrome of free-riding in climate agreements such as the Kyoto Protocol and considers potential structures for overcoming free-riding. This concluding section summarizes the basic approach and conclusions.

The Climate Club

The structure of climate change as a global public good makes it particularly susceptible to free-riding. The costs of abatement are national, while the benefits are global and independent of where emissions take place. An additional complication is that the abatement costs are paid today while most of the benefits of abatement come in the distant future. The present study shows, in a stylized model of costs and damages, that the global non-cooperative carbon price and abatement rate are proportional to the Herfindahl index of country size. This implies, given realistic data, that the global non-cooperative price and control rate will be in the order of one-tenth of the efficient cooperative levels.

We next consider possible mechanisms to combat free-riding and focus on a Climate Club. It is generally assumed that the most effective approach will be to impose trade sanctions on non-participants, and this is the route followed here. Most trade sanctions rely on duties on carbon-intensive goods. For strategic, economic, and technical reasons, this paper instead considers penalties that take the form of uniform ad valorem tariffs levied by club participants on non-participants. In the analysis, the tariff rates vary from 0% to 10%. It is further assumed that a climate treaty will amend trade rules so that retaliation by non-participants is prohibited.

This study assumes that countries adopt an international carbon-price target rather than a quantity target as the policy instrument. The assumed target price ranges from \$12.5 to \$100 per ton CO_2. In the experiments, the international target carbon price is always set equal to the global social cost of carbon.

Individual countries are assumed to adopt climate policies that maximize their national economic welfare. Welfare equals standard income less damages less abatement costs less the costs of trade sanctions. We assume a one-shot static game, but this can be interpreted as the stage game of a repeated game. The equilibrium, described as a *coalition Nash equilibrium,* is a coalition of countries that is stable against any combination of joiners and defectors. The equilibrium is calculated by an evolutionary algorithm that tests each coalition against a random collection of countries that can defect and join.

The study introduces a new approach called the TRICE model (Trade in the Regional Integrated model of Climate and the Economy). It is a 15-region model with abatement, damages, international trade, and the economic impacts of tariffs. Using an evolutionary algorithm, the model can be used to find stable coalition Nash equilibria.

Qualifications

I begin with qualifications on the results that relate to the data and structural parameters. The data on output, CO_2 emissions, and trade are relatively well measured. The global SCC is uncertain but can be varied as shown in the different experiments. The national SCCs are also uncertain, but since they are all small relative to the global SCC, their exact magnitudes are not critical for the findings. Other structural uncertainties relate to the abatement cost function and the optimal tariff rate.

Moreover, these results are presented in the spirit of an extended example used to clarify the realities of international agreements rather than as a concrete proposal for a climate treaty. A Climate Club of the kind analyzed here raises central issues about the purpose of the global trading system, about the goals for slowing climate change, about the justice of a system that puts all countries on the same footing, and about how countries would actually negotiate such a regime. The dangers to the world trading system of such a proposal are so important that they must be reiterated. Today's open trading system is the result of decades of negotiations to combat protectionism. It has undoubtedly produced large gains to living standards around the world. A regime that ties a climate-change agreement to the trading system should be embraced only if the benefits to slowing climate change are clear and the dangers to the trading system are worth the benefits. If incorporating a trade-sanction mechanism is the only viable option to overcome free-riding in climate treaties, and failure to slow climate change poses grave threats to human and natural systems, then changing the rules for international trade would be the price that nations need to pay to protect the global environment.

Results

The first major result is to confirm that a regime without trade sanctions will dissipate to the low-abatement, non-cooperative (NC) equilibrium. This is true starting from a random selection of participating countries. More interestingly, starting from the Kyoto coalition (Annex I countries as defined by the Kyoto treaty) with no sanctions, the coalition always moves to the NC structure with minimal abatement.

A second set of results concerns the impact of different Climate Club parameters on the participation structure. The participation rate and the average global carbon price rise with the tariff rate. For the lowest target carbon prices ($12.5 and $25 per ton), full participation and efficiency are achieved with relatively low tariffs (2% or more). However, as the target carbon price rises, it becomes increasingly difficult to attain the cooperative equilibrium. For a $50 per ton target carbon price, the Club can attain 90+ percent efficiency with a tariff rate of 5% or more. However, for a target carbon price of $100 per ton, it is difficult to get much more than the non-cooperative abatement.

Why is it so difficult to attain an efficient coalition with high social costs of carbon even with high penalty tariffs? The reason is that the gap between the cooperative and the non-cooperative equilibrium rises sharply as the global SCC increases. Take the case of a large country like China or the U.S. For these countries the national SCC might be 10% of the global SCC. For a global SCC and target price of $25 per ton, participation would require increasing the domestic carbon price from $2.5 to $25, while a global SCC of $100 would require increasing from $10 to $100. Because abatement costs are sharply increasing in the target carbon price, this implies that the costs of cooperation become much larger as the target carbon price rises. On the other hand, the costs of trade penalties associated with non-participation are independent of the global SCC. The impact of the gap between national and global SCC is reinforced if the higher SCC leads to lower participation of other countries, which in turn lowers the bite of trade sanctions. So the national cost-benefit tradeoff tilts toward non-participation as the international target carbon price rises.

A related question is whether a trade-penalty-plus-carbon-price regime can survive into the future with the rising carbon prices that are generally associated with an efficient climate-change program. The answer to this question involves the relationship between the growth of the efficient carbon price and the growth of national and world trade. Efficient carbon prices rise over time, but so do trade and output. What is the relationship between these variables?

We can examine this question in the context of the carbon price and world output in the DICE-2013R model (Nordhaus 2014). Assuming that international trade rises at the same rate as world output and its composition is unchanged, we find that the optimal carbon price would need to rise by one-fifth relative to output and trade over the period to 2100 – so for example from \$25 to \$30 per ton. If the policy were to keep within a 2 °C upper temperature limit, the target carbon price would start higher (in the neighborhood of \$50 per ton CO_2), but it would grow more slowly than world GDP. These calculations indicate that global SCC and target carbon prices in the range of \$25 to \$50 per ton CO_2 are the most relevant over the coming years for most current policy proposals. At moderate tariff rates, the regimes would continue to induce high participation rate with continued economic growth.

We can also examine the patterns of gains and losses. Here, we measure the impact relative to the non-cooperative equilibrium. Note as well that these results assume no transfers among countries. The benefits are widely distributed among countries. The only regions showing a substantial number of losses across regimes are Eurasia and South Africa; here the losses are small and hold in about half the regimes. There are no regimes with aggregate losses.

We can look at the distribution of gains and losses to determine whether a Climate Club would be attractive to most countries relative to existing arrangements. For all cases with full participation, all regions would prefer at least a weak regime with penalties to a regime with no penalties. Paradoxically, this is the case even though not all countries participate. The reason is that the gains from some countries taking strong mitigation measures outweigh the losses from the tariffs for non-participants as long as the tariff rate is not too high. This powerful result indicates that a regime with sanctions should be attractive to all regions as long as the sanctions are not overly forceful.

Our calculations indicate that virtually all regimes display unique and stable coalition-Nash equilibria. A few regimes cycle between similarly-sized quasi-stable coalitions.

Bottom line

Here is the bottom line: The present study finds that without sanctions there is no stable climate coalition other than the non-cooperative and low-abatement coalition. This conclusion is soundly based on public-goods theory, on the TRICE model simulations, on the history of international agreements, and on the experience of the Kyoto Protocol.

The analysis shows how an international climate treaty that combines target carbon pricing and trade sanctions can induce substantial abatement. The modeling results indicate that modest trade penalties on non-participants can induce a coalition that approaches the optimal level of abatement as long as the target carbon price is less than $50 per ton range. The regime is sustainable as long as world trade grows as fast as the optimal carbon price. Such a regime would have incentives favorable for attracting a large majority of countries. The attractiveness of a Climate Club must be judged relative to the current approaches, where international climate treaties are essentially voluntary and have little prospect of slowing climate change.

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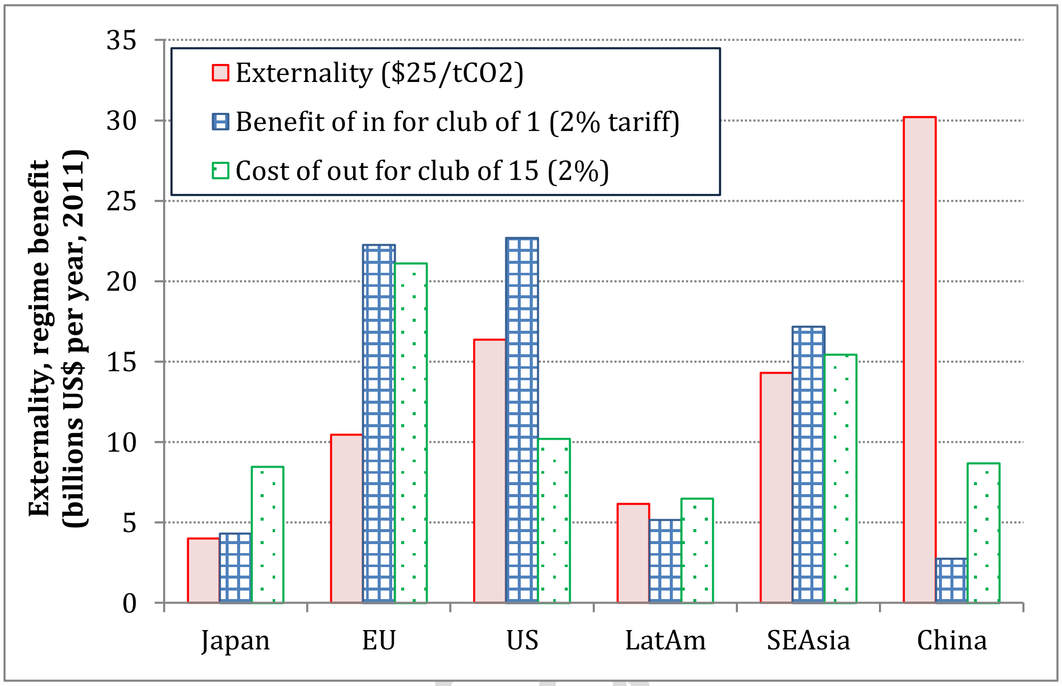

Figure 1. Comparison of the transnational externality and the impacts of penalty tariffs by region

The left-hand externality bar shows the transnational spillover for each region for a $25 per ton global social cost of carbon. The middle benefit bar shows the benefit of participating in a Climate Club with a penalty tariff of 2% for clubs of 1 (that is, the region is the only participant). The right-hand cost bar shows the cost of not participating in a Climate Club with a penalty tariff of 2% for clubs of 14 (that is, the region is the only non-participant).

[Source: exter-prog-simn15-102714c.xlsm, exter2]

		Importing countries	
		Participants	Non-participants
Exporting countries	Participants	No penalty	No penalty
	Non-participants	Penalty	No penalty

Figure 2. Penalty structure in the Climate Club

The matrix shows the structure of penalties in the Climate Club. For example, the lower left cell indicates that when exporting countries are non-participants and importing countries are participants, trade of exporters is penalized. In all other cases, there are no penalties.

[Source: example coalition matrix 033114.xlsx, table 1]

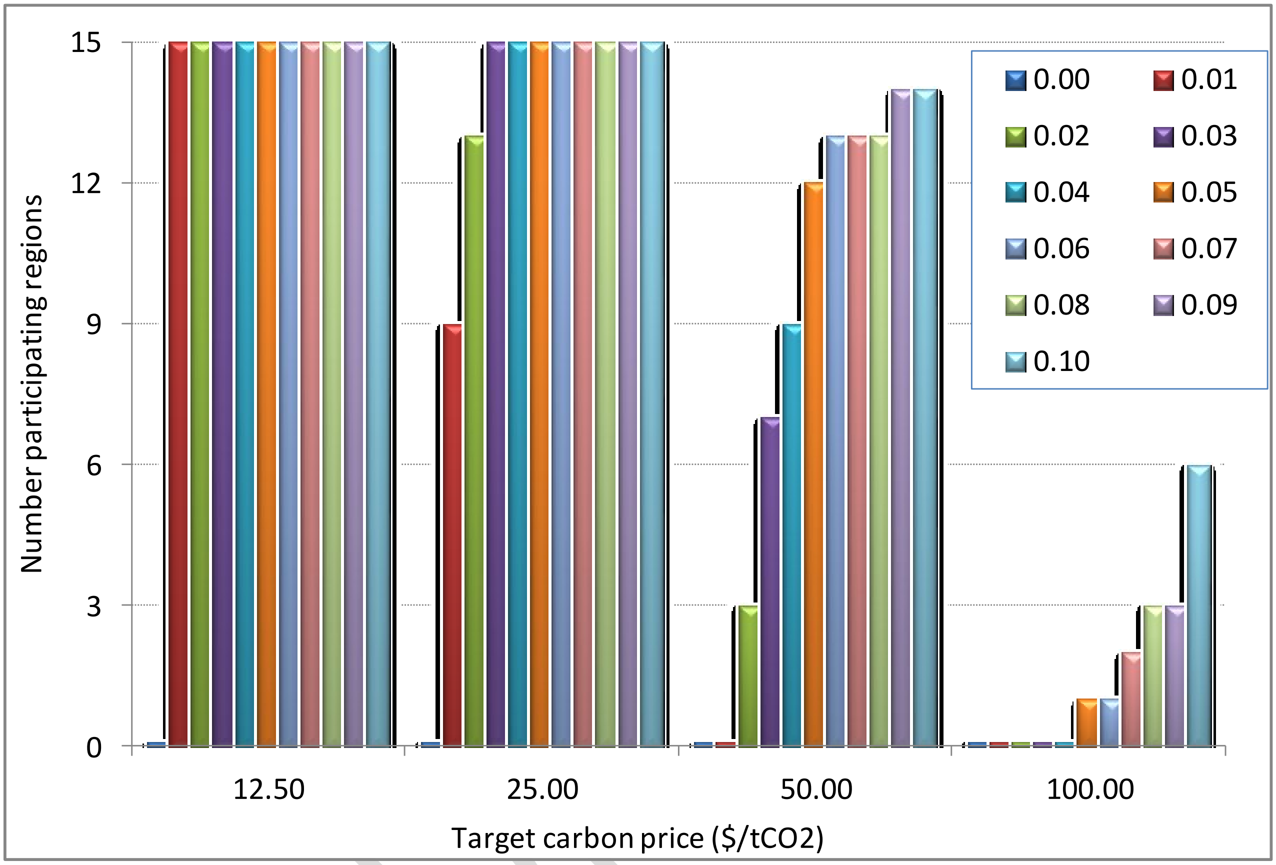

Figure 3. Number of participating regions by international target carbon price and tariff rate

This and the following figures have the following structure. The four sets of bars are the model results for four different global SCCs, running from left to right as shown on the bottom. The eleven bars within each set are the penalty tariff rates, running from 0% to 10%. Note that each set has zero participants for a 0% tariff. The vertical scale here is the number of participants, while the following graphs show other important results.

[Source: res-simn15-102714d.xlsm; page graph]

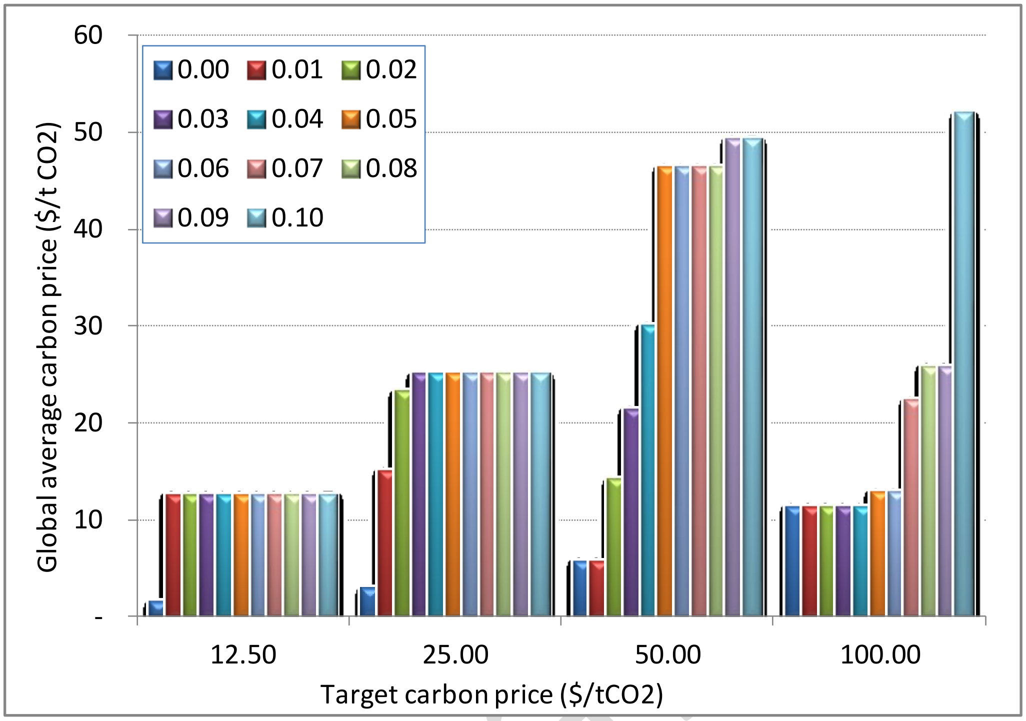

Figure 4. Globally averaged global carbon price by target carbon price and tariff rate

This graph shows the global (weighted average) carbon price for each regime. Weights are actual 2011 industrial CO_2 emissions. The far left bar for each set is the non-cooperative carbon price. For the interpretation of the graph, see Figure 3.

[Source: res-simn15-102714c.xlsm; page graph]

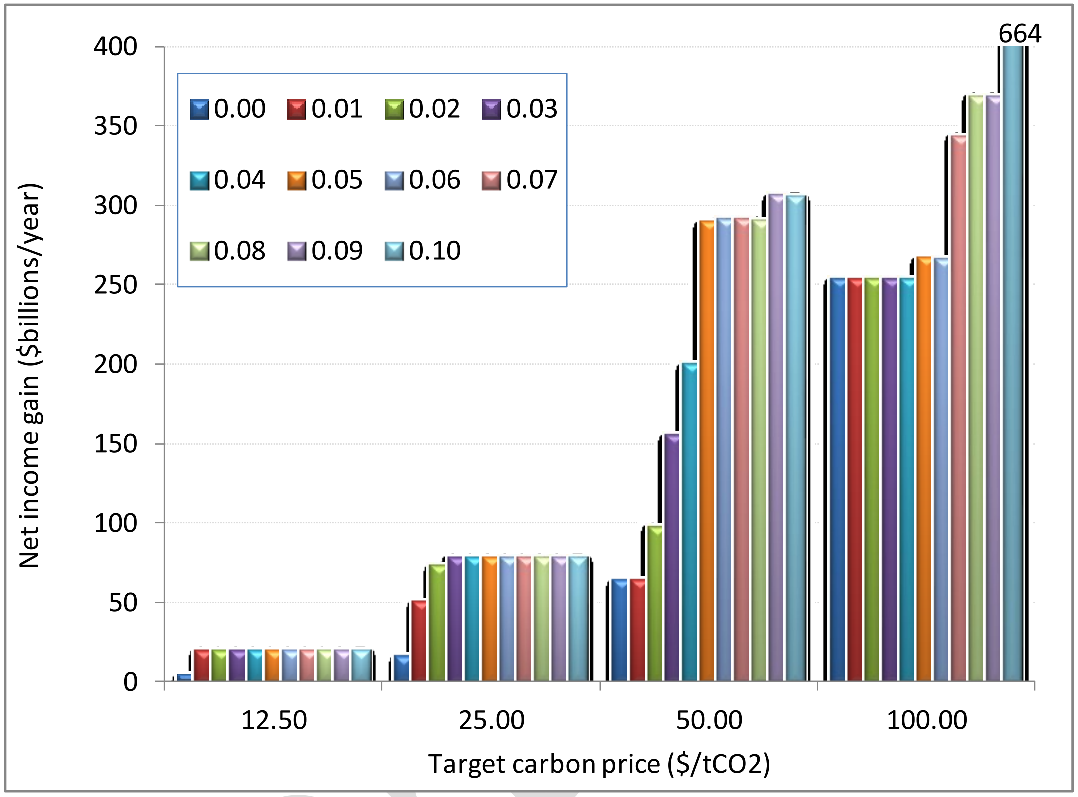

Figure 5. Net economic gains from different regimes

Gains are global total in 2011 US international $. In each case, the gain is relative to zero abatement. The total includes abatement costs, damages, and trade inefficiencies. Note that the far left bar for each group is the gain in the non-cooperative (zero participation) outcome. For the interpretation of the graph, see Figure 3. Note that the graph is truncated at $400 billion at the top, with the figure for highest benefit +regime shown.

[Source: res-simn15-102714c.xlsm; page graph]

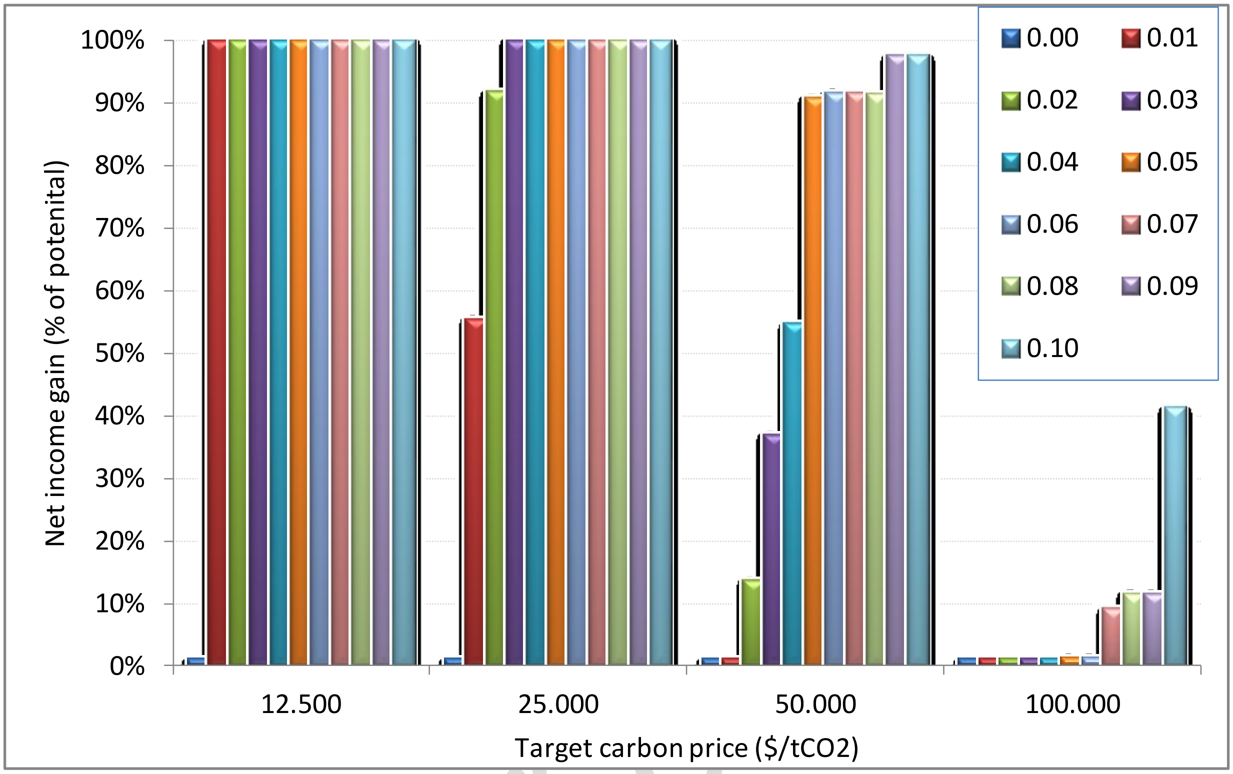

Figure 6. Percent of potential gains from cooperation achieved by different regimes

Bars show the global gain in each regime relative to the non-cooperative outcome as a percent of the difference between the 100% cooperative and the non-cooperative result. Gains are as defined in Figure 5. For the interpretation of the graph, see Figure 3.

[Source: res-simn15-102714c.xlsm; page graph]

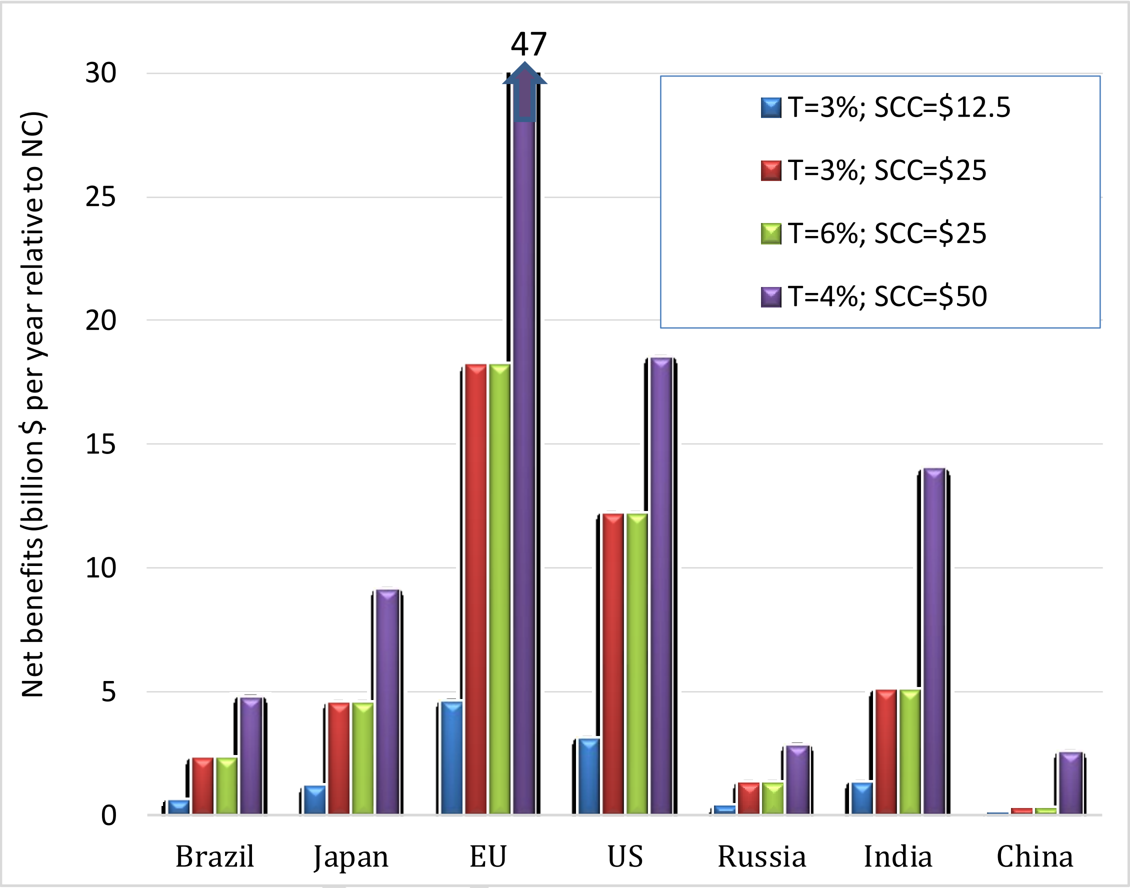

Figure 7. Winners and lose from the Climate Club

Estimates show the gains for regions in four selected regimes. The gains are relative to the non-cooperative regime and are in 2011 US international $ per year. The graph is truncated at $30 billion to increase the scale.

[Source: res-simn15-102714c.xlsm; page impact2]

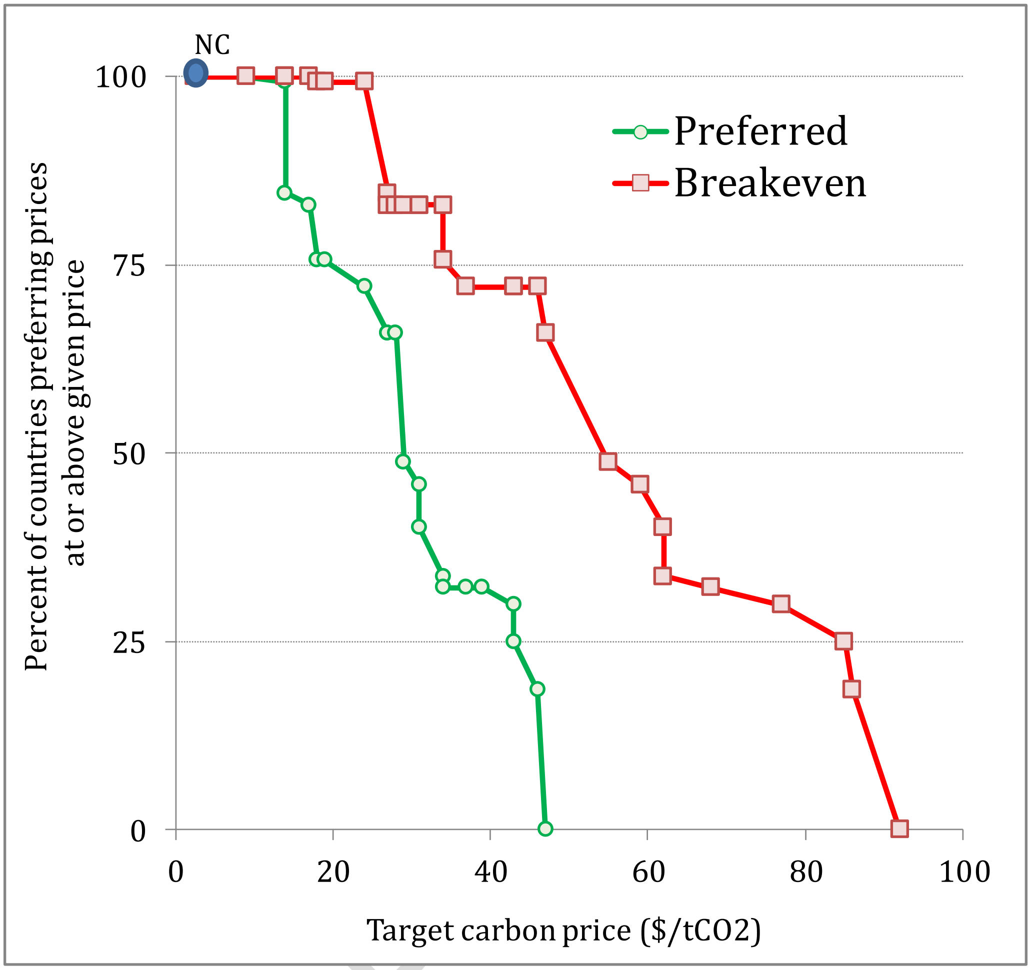

Figure 8. Regional preferences for target carbon price

For a regime with a global SCC of $25 and 100% participation, countries will have differing preferences on the international target carbon price. The lines show the percent of countries (on the left scale) that would be benefitted by a given target carbon price (shown on the horizontal scale). The point marked *NC* at the upper left is the non-cooperative carbon price in this case. The line to the left shows the distribution of preferred carbon prices; the line to the right shows the breakeven carbon prices (the prices at which countries are indifferent between the regime with the target price and the non-cooperative price).

[Source: 25scc national votesv6.xlsx; page Graph]

Penalty tariff rate	US is participant				US is not a participant				Net effect of participation
	Abatement	Damages	Trade	Net benefits	Abatement	Damages	Trade	Net benefits	
0%	-11.9	10.7	0.0	-1.2	-0.3	7.3	0.0	7.0	-8.2
4%	-11.9	10.7	36.7	35.5	-0.3	7.3	-15.6	-8.6	44.1

Figures in billions of 2011 $ from the TRICE model below for a global SCC of $25 per ton of CO_2.

All figures are positive for benefits and negative for costs.

Table 1. Effects of participation in numerical example

This table provides an illustration of the economic effects of participation for the US with and without a penalty tariff. The difference between the two lines is the impact of the penalty tariff. With a penalty tariff, the global externality is effectively internalized, giving incentives for self-interested countries to participate in the Climate Club.

[Source: numerical example 102914.xlsx; page table]

Region	Percent of regimes where participate
Canada	88
EU	83
Mideast	75
Japan	73
LatAm	73
SEAsia	73
SSA	70
US	70
ROW	70
Russia	63
China	63
Brazil	60
Eurasia	60
India	53
Safrica	45
Sum	68

Table 2. Participation rates by region across all 4 x 10 regimes with penalty tariffs.

[Source: res-simn15-102714c.xlsm; page: graph]

Region	Global target carbon price that maximizes domestic welfare for club of 15 ($/tCO2)
South Africa	9
Eurasia	14
China	14
SE Asia	17
Russia	19
ROW	24
US	28
Brazil	29
Latin America	31
India	31
Canada	34
Sub-saharan Africa	39
Japan	43
Mideast	43
EU	46
Memorandum items:	
Global SCC	25
Average preferred price	
GDP weights	30
Population weights	28
Median preferred price	
GDP weights	28
Population weights	29

Table 3. Country preferred international target carbon prices (for global SCC of $25)

What international target carbon price would regions prefer when the global SCC is $25 per ton? For example, the US national welfare is highest when the target price is $28 per ton. Countries with high damages and low abatement costs such as the EU costs prefer high target prices.

[Source: 25scc national votesv6.xlsx; sheet Table3]