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On the efficiency gains of emissions trading when climate deals are non-cooperative

by

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On the efficiency gains of emissions trading when climate deals are non-cooperative[*]

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Abstract

This paper studies, in a numerical environment, climate treaties with emissions trading when national quotas result from strategic individual choice. We find that the larger the number of parties to the deal, the smaller are the emissions reductions and the lower the welfare. If insisting on stability with respect to participation, climate treaties involve few parties and yield practically no emissions reductions. While these results contrast with some optimistic studies, our numerical example confirms established results if modelling the problem in the more traditional sense.

JEL classification: C72, D62, Q54.

1 Introduction

The efficiency arguments for *international emissions trading* when the initial allocation of permits is considered as already given are well established. Quite simply, voluntary exchange cannot harm any trading party. Moreover, this policy instrument has further been identified as a promising tool when the initial allocation is not already given, but rather is part of the problem. The

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reason is that it can serve as a vehicle to facilitate side payments in international negotiations. Such payments have the potential to broaden international participation and deepen the emissions cuts. This conclusion applies regardless of whether the underlying model of international negotiations is presumed to follow the early works by Barrett [1] and Carraro and Siniscalco [5] or whether one adopts Chander and Tulkens' [7] alternative perspective.[1] A common assumption in these and other studies on international environmental agreements is that the aggregate emissions target is set to a level that maximizes the *collective* objectives of those parties signing a deal.

However, several decades of international climate talks have resulted in little agreement other than the Kyoto Protocol. When looking at the aggregate target of those countries with quantified commitments that ratified that treaty, a large literature has concluded that the resulting aggregate target is not substantially different from their business as usual emissions; see, e.g., Springer [22] for a survey. Hence, although well furnished with good intentions, the international climate talks thus far have resulted in few outcomes that resemble efficient bargaining and collective behaviour. Despite this, emissions trading as a policy tool has emerged at centre stage.

The purpose of this paper is to examine some possible consequences of emissions trading in a fairly fragmented world where governments struggle to get together and maximize their collective objectives. Rather, we take it that decisions are better reflected by governments optimizing on *individual* concerns—along the lines considered in the studies by Helm [14] and Carbone et al. [3] among others.[2] In this type of setting, governments that decide to take on quantified international commitments select their quotas individually while still recognizing each other's targets as transferable documents that are suitable for compliance—the latter presumed to be enforced.

What could such a setting possibly deliver in terms of overall efficiency? To address this question, it is best to take the classical non-cooperative outcome of reference as a point of departure where emissions are reduced to the level where the marginal abatement cost in a country is equated to the domestic marginal damage cost. There are two sources of inefficiencies associated with the latter outcome. First, global emissions are too large. Second, they are inefficiently allocated. When governments select their quotas and then engage in trade, the differences in marginal emissions reduction costs will tend to be

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[1] More recent and relevant studies dealing with asymmetric countries and side payments possibly via emissions trading in these two traditions of literature include Carraro et al. [4], McGinty [18], Brechét et al. [2], Chander [6] and Flåm [12].

[2] See also Copeland and Taylor [8], Cramton and Stoft [9], [10], Holtsmark and Sommervoll [15] and Godal and Holtsmark [13] for closely related literature.

traded away, reducing the second source of inefficiency. Therefore, the merits of the overall outcome are dependent on aggregate emissions, as given by the sum of the targets. As Helm [14] has already established that the total effect is sensitive to parameter values, we follow Carbone et al. [3] in relying on numerical simulations. Our models focus on different aspects; in particular, they consider more goods whereas we consider more players.

Among the 4083 possible climate deals between subgroups of the 12 major greenhouse-gas-emitting countries included in our analysis, we identify six treaties that satisfy the property that no member wants to exit (internal stability). Each of the six treaties involves only two parties and they all bring the economy very close to the no-trade outcome of reference. One of the six treaties is also externally stable in that no non-signatory wants to enter. Putting issues of participation stability aside, we find that the larger the number of participants, the lower the global welfare. Most arrangements, including that with full participation, imply efficiency levels below the classical non-cooperative (no-trade) solution. A main explanation for the latter results is that the permit price will equal the *average* marginal climate cost of the countries that sign the deal, as noted by Helm [14]. As such, we do not think it is surprising that behaviours that fall short of joint maximization yield inefficient outcomes. Nevertheless, our results are in contrast to the rather optimistic results of Carbone et al. [3] concerning what *international emissions trading* may possibly accomplish in a fragmented world.

For comparisons, we also use our example to illustrate the more classical models of international environmental agreements where signatories maximize their joint objectives so that the permit price will equal the *aggregate* marginal damage costs for those signing a deal. When modelling the situation as a 'cartel formation game', our results are in line with similar studies, e.g. Carraro et al. [4], McGinty [18] and Brechét et al. [2]. We also compute a treaty that is stable in the sense of the 'gamma core', which therefore is also efficient.

A property that comes through in many of our stable agreements—however defined—is that money is transferred from countries that presumably are most heavily affected by climate change, such as China, India and Europe, which pay those parties that incur much of the implementation costs, such as Russia and the USA. This illustrates that transfers the other way may be misaligned with participation incentives.

The paper is organized as follows. In Section 2, we present the economic environment and spell out the theories—all well established—that we shall carry out simulations on. Section 3 briefly discusses how the model was parameterized, with further details relegated to a supplement. Section 4, the heart of the paper, offers results and Section 5 concludes.

2 The economic environment and the models

2.1 The setting

There is a fixed and finite set I of countries. Each country $i \in I$ has an economic benefit $\pi_i(e_i)$ of discharging e_i units of greenhouse gases into the atmosphere, and is adversely affected by climate damages $v_i(e)$, where $e := \sum_{i \in I} e_i$. In our simulations, π_i is increasing and concave in a quadratic manner up to business as usual emissions, and v_i is linear with $v_i'(e) > 0$ for all $i \in I$.

Before we turn to the various games to be considered, we first recall two well-known outcomes of reference.

$$\text{Emissions } (\bar{e}_i)_{i \in I} \text{ are } \textit{Pareto efficient} \text{ if } \pi_i'(\bar{e}_i) = \sum_{j \in I} v_j'(\bar{e}) \tag{1}$$

for all $i \in I$. A no-trade, non-cooperative

$$\textit{Nash equilibrium} \text{ profile } (e_i^*)_{i \in I} \text{ satisfies } \pi_i'(e_i^*) = v_i'(e^*) \tag{2}$$

for all $i \in I$. In (1), $\bar{e} := \sum_{i \in I} \bar{e}_i$ and similar shorthand notation applies for e^* in (2).

2.2 Climate deals with individual maximization

This section restates the model of main interest originally formulated by Helm [14]. The game has a three stage structure. First, parties—seen as governments—decide whether or not they want to participate in a climate treaty with international emissions trading, thereby belonging to a list $C \subseteq I$.[3] Second, every government selects a quota ω_i of permits that is transferred to domestic economic agents named firms. Third, firms select emissions e_i where those that belong to C can trade permits among each other, while others cannot.

As customary, we start with the **last** stage of the game. To avoid unnecessary cluttering of notations, all firms within a country are represented via a single entity named a firm. This agent takes the permit price p and its quota

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[3] In the next subsection, we will follow the standard terminology and refer to C as a *coalition*. In the current subsection, such usage is somewhat misleading, as no group of countries maximize their joint objectives.

ω_i as given, and if its government has decided to participate in the treaty, it solves

$$\max_{e_i}\{\pi_i(e_i) + p\cdot(\omega_i - e_i)\} \text{ for each } i \in C,$$

where p clears $\sum_{i\in C} e_i = \sum_{i\in C}\omega_i$. A firm in a country that is not participating in trade sets $e_i = \omega_i$.

At the intermediate **second** stage, governments select their quotas. If government $i \in C$ then this choice solves

$$\max_{\omega_i}\{\pi_i(e_i) - v_i(e) + p\cdot(\omega_i - e_i)\} \text{ for all } i \in C, \tag{3}$$

recognizing that p and e will depend on the selected ω_i. A government not in C simply solves

$$\max_{\omega_i}\{\pi_i(e_i) - v_i(e)\}. \tag{4}$$

Before proceeding with stage one of the game, we state the first order necessary optimality conditions for the two stages. For each $i \in C$,

$$\pi_i'(e_i) = p \text{ and } \textstyle\sum_{j\in C} e_i = \sum_{j\in C}\omega_i, \tag{5}$$

$$\pi_i'(e_i) - v_i'(e) + \tfrac{\partial p}{\partial \omega_i}(\omega_i - e_i) = 0 \tag{6}$$

where

$$\frac{\partial p}{\partial \omega_i} = \frac{1}{\sum_{j\in C}\frac{1}{\pi_j''(e_j)}}.$$

For each $i \notin C$

$$e_i = \omega_i \text{ and } \pi_i'(e_i) - v_i'(e) = 0.$$

In (6), we have made use of the first equality in (5). For readers interested in more details, please see Helm [14].

We complete with the **first** stage of the game, aimed at finding a stable list C of countries subscribing to the treaty. Denote by $\Pi_i(C)$ the value function associated with government i's objective in problem (3) when $i \in C$ and (4) otherwise. As customary, C is declared *internally* stable under an open membership rule if

$$\Pi_i(C) \geq \Pi_i(C \setminus \{i\}) \tag{7}$$

for all $i \in C$ so that a member does not prefer to leave it. Furthermore, C is *externally* stable under an open membership rule if for each $i \notin C$

$$\Pi_i(C \cup \{i\}) \leq \Pi_i(C), \tag{8}$$

implying that no outsider is keen on becoming a member. A coalition C is then *stable* if it is both internally and externally stable; d'Aspremont et al. [11] is a standard reference.

The external stability concept has some properties that are not immediately appealing. For instance, if a country wants to join a treaty, but no participating country would appreciate its presence, it seems plausible that it could be blocked from becoming a member. Following Sáiz et al. [21] among others, this motivates some modified notions of external stability.

A list C is *unanimously externally* stable if for every $i \notin C$ for which

$$\Pi_i (C \cup \{i\}) \geq \Pi_i (C) \tag{9}$$

if any, there exists at least one $j \in C$ for which

$$\Pi_j (C \cup \{i\}) < \Pi_j (C) . \tag{10}$$

As this unanimity rule is founded on a fairly stringent—albeit often applied—consensus principle, we shall also make use of the following alternative formulation. If for every $i \notin C$ for which (9) is true, condition (10) holds for a majority of those that belong to C, then C is *externally* stable via *majority.*

2.3 Models for comparisons

Before we turn to our numerical example, we briefly recall the two arguably most studied models of international environmental agreements. Both have a two stage structure where at the second stage, members of what we now name a coalition $C \subseteq I$, which was formed at stage one, select a vector of emissions $(e_i)_{i\in C}$ that

$$\text{maximizes} \sum_{i\in C} \{\pi_i (e_i) - v_i (e)\}. \tag{11}$$

Each country that does not belong to C finds an e_i that solves

$$\max\{\pi_i (e_i) - v_i (e)\}. \tag{12}$$

Here, coalition members and outsiders are also affected by each other's decision via the common environment. This externality is again accounted for in the format of a non-cooperative game, where the coalition and the outsiders take the choices made by others as given. The necessary first order conditions are therefore given by

$$\left.\begin{array}{lll} \pi_i' (e_i) = \sum_{j\in C} v_j' (e) & \text{for all } i \in C & \text{and} \\ \pi_i' (e_i) = v_i' (e) & \text{for all } i \notin C. & \end{array}\right\} \tag{13}$$

Cartel stability
If side payments (or transfers) between members of a coalition are banned, then the same notions of internal and external stability as discussed in the previous subsection can be directly applied. Conversely, if monetary transfers between parties take place, possibly accompanied by permits flowing the other way, a broader notion of internal stability becomes useful. Following Carraro et al. [4], a coalition is said to be *potentially internally stable* if the payoff to the whole coalition $\Pi_C(C) := \sum_{i\in C}\Pi_i(C)$ satisfies

$$\Pi_C(C) \geq \sum_{i\in C}\Pi_i(C\setminus\{i\}).$$

This means that if a coalition is potentially internally stable, it generates a sufficient surplus that can be allocated among its members so that no party can benefit from leaving.

Core stability
Underlying the cartel stability concept is the assumption that if a member leaves the coalition, the rest of the coalition remains intact. If we instead assume the remaining coalition disintegrates when a member leaves, then one can identify an element in the so-called gamma core (Chander and Tulkens [7]). More precisely, let $(W_i)_{i\in I}$ be a vector of payoffs where the elements add up to the society-wide payoff that is the most achievable: $\sum_{i\in I} W_i = \Pi_I(I)$. If such a vector satisfies

$$\sum_{i\in C} W_i \geq \Pi_C(C) \text{ for all } C\subseteq I,$$

then it belongs to the core.

When damages are linear, as they will be in our numerical experiments, there is a particular and easily computable profile, which satisfies the gamma core stability property; see, e.g. Brechét et al. [2]. It is given by

$$W_i = \pi_i(e_i^*) - v_i(e^*) + \alpha_i\left(\sum_{j\in I}\{\pi_j(\bar{e}_j) - v_j(\bar{e})\} - \sum_{j\in I}\{\pi_j(e_j^*) - v_j(e^*)\}\right) \tag{14}$$

for all $i\in I$, where $\alpha_i := v_i'(e_i)/\sum_{j\in I} v_j'(e_j)$ is agent i's share of total marginal damage. Formula (14) quite simply says that a country receives its non-cooperative Nash payoff plus a share of the gains from cooperation in proportion with how severely the country is affected by climate change.

3 Parameterization and benchmarks

This section starts by briefly discussing how the model was parameterized, with the details relegated to a supplement. Subsequently, we present the two outcomes of reference: the classical non-cooperative Nash equilibrium and the Pareto optimal solution.

The player set: While the world consists of about 190 nations, it is difficult to accommodate that fact in our numerical environment. Our choice of a specific collection of 11 countries, together with Europe (essentially the European Union), was motivated by the desire to include countries that presumably are important in the sense of size when it comes to the issue of climate change.[4] In that respect, our approach is not unique. Furthermore, we contrast some literature by hesitating to model multinational regions other than Europe as individual players. In fact, it is this lack of collective behaviour that is at the very heart of the problem. For the same reason, those countries that are not represented individually in the model (i.e. the rest of the world) are not represented as a single decision maker but instead excluded from the model.

The benefit function $\pi_i(e_i)$: We implemented carbon taxes in the intertemporal computable general equilibrium model MERGE of the world economy developed by Manne and Richels [16], [17] to obtain simulation data for the year 2020. These data indicate how much emissions would be reduced in each MERGE region for various levels of a carbon tax. Simple OLS regressions on these data indicate that marginal benefits (i.e. marginal abatement costs) have a good linear fit for taxes in the range 0–250 US dollar per tonne of carbon. More specifically, the region with the poorest fit (Japan) had an R-square equal to 0.82, with all others being above 0.9. The marginal benefit function is given by $\max\{a_i - c_i e_i, 0\}$ where the parameters $a_i, c_i > 0$ and where business as usual emissions are given by a_i/c_i. Benefits, $\pi_i(e_i)$, are normalized to zero at business as usual emissions. Thus, they become negative and are equivalent to abatement costs.

The damage function $v_i(e)$: The damage function is assumed linear for all countries so that $v_i'(e) > 0$ is simply a constant, and its value is taken from simulation results of the RICE model by Nordhaus [19][5]. In particular, we used results from RICE to distribute estimates of global marginal damage.

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[4] The regions included in our analysis comprise about 78 per cent of global emissions.

[5] The stated reference offers a description of the sister model of RICE, namely DICE. We used results from the RICE model, downloaded from Nordhaus' webpage http://nordhaus.econ.yale.edu/RICEModelDiscussionasofSeptember30.htm in February 2010.

As climate damages in RICE are at the low end compared with other studies, we also made use of the literature review by Tol [23] dealing with studies of the global marginal damage of greenhouse gas emissions.

Both the MERGE and the RICE models have aggregated the world into only a few regions. We used data for gross national income taken from the World Bank to disaggregate the benefit and damage functions. Precisely how this was done is explained in the supplement. The parameters used in the numerical analysis are given in Table 1 and apply to the year 2020. In the Tables and Figures, we use the following abbreviations: M is million, B is billion, t is (metric) tonne, C is carbon and yr is year.

Table 1 about here.

Table 2 reports key figures for emissions reductions and payoffs in the non-cooperative Nash equilibrium as well as the Pareto optimum.

Table 2 about here.

Table 2 shows that without any form of climate treaty (non-cooperative Nash), global emissions reductions are 1.5 per cent in total, as compared with business as usual emissions. However, the efficient level of global reductions is 10.7 per cent. A quite large share of these additional reductions occur in the USA. The increased reductions from Nash to Pareto increases global welfare from –634 to –608 billion US$ per year, so that the total gain available with an efficient climate policy is about 26 billion US$ per year.

What is notable is the distribution of these efficiency gains given in the last column in Table 2. Europe, China and India gain most of the benefits in the efficient solution, while the USA and some other countries in fact are worse off (when not receiving side payments). The explanation behind this result lies in the third column of Table 2, showing that the USA carries by far the largest emissions reductions compared with the Nash equilibrium point. Furthermore, although the USA will benefit from lower damages, these are not sufficient to cover the increased abatement costs. Countries such as China and India carry out more modest reductions, but because they are more severely affected by climate change, their benefits from the Pareto efficient solution become more pronounced.

For later discussions on gains in environmental effectiveness and economic efficiency associated with various partial climate agreements, we define two indices. Recall that $\bar{e}$ and e^* have been defined as global emissions under Pareto optimality (1) and the classical non-cooperative Nash equilibrium (2), respectively. Write $\bar{\Pi}$ and Π^* for the global welfare (the sum of individual payoffs Π_i) associated with these profiles. Moreover, let $e_I(C) := \sum_{i \in I} e_i(C)$ be the global emissions when a particular list of countries sign a climate deal, and recall that $\Pi_I(C)$ is the global welfare similarly defined $(= \sum_{i \in I} \Pi_i(C))$. The environmental effectiveness Φ_C^e and economic efficiency Φ_C^{Π} of a particular climate treaty are then defined as

$$\Phi_C^e := \frac{e_C(C) - e^*}{\bar{e} - e^*} \text{ and } \Phi_C^{\Pi} := \frac{\Pi_C(C) - \Pi^*}{\bar{\Pi} - \Pi^*} \tag{15}$$

respectively. Construed in this way, both indices take the value zero in the Nash equilibrium and one in the Pareto optimum. A negative number indicates that emissions (welfare) are larger (smaller) than that associated with the non-cooperative Nash. Finally, note that as our model contains 12 countries, there are 4083 possible coalitions containing at least two countries.

4 Results

4.1 The main model

This section reports the simulation results, where we start with the main model of interest. We then discuss the two other models before we conduct some sensitivity simulations.

Figure 1 about here

In Figure 1, the results for all 4083 possible coalitions are plotted, each representing the outcome for a coalition when applying the model by Helm [14]. Of these coalitions, 4077 are not internally stable and depicted by empty grey triangles. Note that not all of them appear unfilled; however, this simply reflects that there are many stacked closely together. We see that they mainly have an efficiency index less than zero, that is, they are less efficient than the classical non-cooperative case without any emissions trading. Furthermore, there is a tendency that the larger the coalition, the less efficient the outcome.

There are six coalitions that are internally stable, all involving only two parties. For all practical purposes, they have similar economic efficiency indices that are positive yet close to zero.[6] Thus, in the figure, they appear as

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[6] Stable treaties will always have a positive efficiency index. Conversely, there must be at least one country that is worse off. Such a country would therefore prefer not to be part of a climate deal, making it internally unstable.

a single point. Among these six coalitions, one is also externally stable, thus stable. The details of these six coalitions, together with some others for later comparison, are given in Table 3.

Table 3 about here

We see from Table 3 that none of the internally stable coalitions includes major parties such as the USA, Europe, China or India. What is common for five of the coalitions is Russian membership together with one other player and where Russia is the permit seller. This illustrates a point made by Helm [14, Proposition 1], in that 'low damage' countries become permit exporters, and 'high damage' countries permit importers. Moreover, Russia's trading partner is a relatively small country with lower business as usual emissions and higher marginal damages as compared with Russia. The only stable coalition is Russia and Australia, with practically no emissions reductions or efficiency gains. Also worth noting is that a global climate treaty is not stable and rather inefficient.

4.2 Cartel formation game

We shall now look at the cartel formation game, where we start by allowing for side payments.

Figure 2 about here

In Figure 2, agreements that are not potentially internally stable are marked with a grey triangle and potentially internally stable coalitions are marked with a red open triangle that is filled with green if also externally stable. Putting stability requirements aside, we see that in contrast to the previous model, there is a general trend that the larger the coalition, the greater the economic efficiency. This is a result that holds more generally. Recall from (13) that the marginal payoff for all members of a coalition equals the *aggregate* marginal damage of its members. Therefore, if enlarging any given coalition with one more member, then efficiency will unambiguously improve when damages are positive and linear.[7]

Among the 4083 possible coalitions, 1095 are potentially internally stable, 240 of which are also externally stable, and therefore potentially stable under

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[7] This is in contrast to the Helm model, where it follows by adding up (6) for all $i \in C$ and making use of (5) that the common marginal payoff for permit trading parties equals the *average* of their marginal damages.

all definitions of external stability. This means that it is possible to make the coalition stable via side payments. While the general upward efficiency trend also holds for coalitions that are potentially internally stable, there is a trade-off at the frontier. The coalition that delivers the most economic efficiency, which is compatible with stability, consists of merely three players: the USA, Europe and China. There are also larger stable coalitions with up to seven countries, but they yield less efficiency.[8] The details for these three coalitions are given in Table 4, together with the outcomes of those that were stable in the previous subsection.

Table 4 about here

Table 4 shows that the USA–Europe–China coalition delivers an economic efficiency index equal to 45.2 per cent. The underlying figures are such that the USA is worse off than if leaving the coalition, but China and Europe benefit sufficiently to pay the USA for not leaving. Hence, transfers are needed to stabilize the coalition, and they must go from China and Europe to the USA. The intuition for this is very much the same as for some results in the gamma core, to be discussed in the next subsection. Furthermore, there exist stable coalitions with up to seven countries, with USA–Canada–Mexico–Korea–Australia–Russia–China being the one that delivers the most efficiency. Again, China must pay its coalition partners to stabilize the coalition.

If side payments are excluded (and therefore not part of Figure 1 and Table 4), then nine of the 4083 coalitions are internally stable, all with two members. The best performing coalition among these is Europe–China, which produces an efficiency index of 11.9 per cent. Other internally stable coalitions that deliver some emissions reductions are USA–Japan, China–India, the USA–Brazil and the USA–South Africa. The three remaining internally stable coalitions offer efficiency improvements below 1 per cent.

Only one of the internally stable coalitions, when side payments are banned, is also externally stable: China–India, regardless of which notion of external stability is applied. Two other coalitions, the USA–Japan and Japan–South Africa, are stable both via majority and unanimity. To summarize, for the case without side payments, there are few stable coalitions; they involve few parties and deliver very modest efficiency gains.

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[8] Qualitatively speaking, Brechét et al. [2] report results with similar properties concerning efficiency and the number of participators.

4.3 The gamma core

The last theory illustrated in this paper continues with the assumption that members of a coalition are able to maximize their joint objectives, but where the applied stability concept is in accordance with the gamma core. The underlying details of an agreement that satisfies this stability property—thereby being both stable and efficient—are given in Table 5.

Table 5 about here

The first column in Table 5 gives the payoff for each country in the core when applying formula (14). The next column shows how the gains from co-operation are distributed. The figures given in the column labelled 'transfers' describe the flow of money between the countries that are sufficient to secure stability. The most important cash flows go from Europe, China and India towards the USA, and although in smaller amounts, to Russia. These results are counter to some everyday climate politics jargon, which says that industrialized countries must pay for emissions reductions in developing countries to get them on board.

To provide some intuition for these results, we start with the case of the USA and then continue with a well-established general argument. Table 2 illustrates that the USA is worse off with efficient emissions reductions as compared with the Nash equilibrium. The explanation is that a large share of global emissions reductions when aiming for efficiency is required to take place in the USA. The abatement costs associated with these reductions are so large that the resulting improved climate benefits in the USA are not sufficient to compensate for the associated abatement costs. This means that the USA needs to be paid for reducing its emissions in order to find it interesting not to deviate. The payments to the USA typically come from countries that have a significant interest in a better climate (a high marginal damage) combined with the lack of large and relatively inexpensive emissions abatement options. Given the parameters of our model, such countries include China, India and Europe.

While formula (14) clearly shows that all agents are better off in the core as compared with the classical non-cooperative outcome, it is not clear what governs the side payments. However, the applied formula may, as in Chander and Tulkens [7], be rearranged into the following:

$$W_i = \left[\pi_i\left(\bar{e}_i\right) - v_i\left(\bar{e}\right)\right] + \left[\pi_i\left(e_i^*\right) - \pi_i\left(\bar{e}_i\right)\right] - \alpha_i \left[\sum_{j \in I} \pi_j(e_j^*) - \sum_{j \in I} \pi_j(\bar{e}_j)\right]. \quad (16)$$

The first square bracket in (16) is the payoff a country obtains evaluated at efficient emissions, i.e. those that actually materialize. Therefore, the remaining two brackets constitute the transfers, being positive if money is received and negative if paid. As $\pi_i(e_i^*) \geq \pi_i(\bar{e}_i)$, the middle bracket signifies that agent i is compensated for the increased abatement cost associated with cooperation. The last bracket indicates that agents must pay in proportion with their marginal damage. Therefore, countries that are heavily affected by climate change combined with spending little additional resources on abating emissions in moving from the non-cooperative Nash to Pareto optimal emissions will have to pay countries that are not substantially affected by climate change but that are burdened with a large portion of the emissions reduction costs. As such, if poor countries are heavily affected by climate change with few possibilities for reducing their own emissions, they must pay the rich countries for them to reduce emissions, in particular if the latter are not substantially harmed by climate change. As Chander and Tulkens [7, p. 291] explain, "formula (16) ...[is] more in the spirit of the 'victim pays' principle than of the 'polluter pays' principle. This only reflects the fact that the ethical values that inspire the latter are here in opposition to the self-interest considerations that are called on to ensure voluntariness in cooperation and deter free riding."

The final two columns in Table 5 illustrate how the side payment scheme may look if implemented via a permit market, where the price of permits would equal the global marginal damage of climate change, here being US$97 per tonne carbon. The column 'Permit exports' gives the number of permits a country in equilibrium would export, while the 'Initial quota' column gives the initial distribution of quotas prior to trade, and relative to business as usual emissions.

4.4 Sensitivity analysis

The above results rest on many parameters that in reality are not well known. Of importance are the level and the distribution of climate damage. Reported here are some outcomes under alternative assumptions.

Thus far, the aggregate marginal damage has been set to $97 per tonne of carbon. However, if we follow Carbone et al. [3] by replacing that number with 650 but keeping our distribution of the damages, then our results are, qualitatively speaking, not substantially affected. That is, Figures 1 and 2 remain essentially intact. If we instead keep the $97 per tonne carbon figure, the main qualitative picture remains unchanged if we alter the distribution more in line with Carbone et al. [3] as follows: USA 20.9, Canada 2.1, Mexico

0.0, Europe 41.9, Japan 20.1, Korea 2.1China 0.0, India 0.0, Brazil 0.0 and South Africa 0.0. That is, in the Helm model, most coalitions produce an outcome with an efficiency index below the no-trade solution, and there is a tendency that the larger the coalition the lower the efficiency. Nevertheless, there are stable coalitions with up to four players (in contrast to merely two), yet they all have an economic efficiency index below 5 per cent.

5 Summary and concluding remarks

This paper revisited three models dealing with international efforts to reduce greenhouse gas emissions, with the main motivation and focus of the game defined by Helm [14] where quotas are set individually and non-cooperatively. With our parameters, that game yielded little environmental and economic efficiency. These results are less optimistic than those in Carbone et al. [3]. While our analysis did not explicitly account for general equilibrium effects, that of Carbone et al. [3] do, and they emphasize their importance. Our results for the two other models are more in line with the comparable literature. Some models that we did not discuss above include 'farsighted coalition stability' as in Osmani and Tol [20], and the possibility of having multiple coalitions, e.g. Sáiz et al. [21].

Even though the three models we considered produce radically different outcomes, they all seem to have a common property: countries that are heavily affected by damages, but have few opportunities to abate emissions at low costs, must pay countries that are not as substantially affected but have cheap abatement options. The economic intuition for this result is similar to established arguments on comparative advantages in international trade. That this may disagree with other, perhaps ethical, considerations may thus illustrate why climate negotiations thus far have shown little success.

Our analysis has many well-known and obvious shortcomings. To name but a few, we did not consider dynamics and uncertainty. Furthermore, endogenous general equilibrium effects were not accounted for. Further, while we only dealt with 12 major greenhouse gas emitters, we believe that the negative flavour of our results would only be further reinforced if more countries were included in the analysis.

Despite these shortcomings, we emphasize that when international emissions trading is made central in a climate deal, it creates certain incentives that are absent when trade is ruled out. If governments do *not* act on these incentives and rather are able to make the aggregate target sufficiently tight, then the good properties of emissions trading will apply. However, if governments *do* take these incentives into consideration by means of demanding generous quotas, that may undermine the effectiveness of the treaty to such an extent that little will be achieved. It seems to us that anecdotal evidence thus far points towards the latter situation rather than the former, if anywhere at all.

References

[1] Barrett, S. (1994), Self-enforcing international environmental agreements. *Oxford Economic Papers* 46, 878–894.

[2] Bréchet, T., Gerard, F., Tulkens, H. (2011), Efficiency vs. stability in climate coalitions: A conceptual and computational appraisal. *Energy Journal* 32, 49–75.

[3] Carbone, J.C., Helm, C., Rutherford, T.F. (2009), The case for international emission trade in the absence of cooperative climate policy. *Journal of Environmental Economics and Management* 58, 266–280.

[4] Carraro, C., Eyckmans, J., Finus, M. (2006), Optimal transfers and participation decisions in international environmental agreements. *Review of International Organizations* 1, 379–396.

[5] Carraro, C., Siniscalco, D. (1993), Strategies for the international protection of the environment. *Journal of Public Economics* 52, 309–328.

[6] Chander, P. (2003), The Kyoto Protocol and developing countries: Strategy and equity issues, Chapter 13 in Toman, M.A., Chakravorty, U., and Gupta, S. (eds) India and global climate change: Perspectives on economics and policy from a developing country, Resources for the Future, Washington DC, USA.

[7] Chander, P., Tulkens, H. (1995), A core-theoretic solution for the design of cooperative agreements on transfrontier pollution. *International Tax and Public Finance* 2, 279–293.

[8] Copeland, B.R., Taylor, M.S. (1995), Trade and transboundary pollution. *American Economic Review* 85, 716–737.

[9] Cramton, P., Stoft, S. (2010a), International climate games: From caps to cooperation, Research Paper 10-07, Global Energy Policy Center, USA (http://www.global-energy.org/lib).

[10] Cramton, P., Stoft, S. (2010b), Price is a better climate commitment. *The Economists' Voice* 7: Iss. 1, Article 3.

[11] d'Aspremont, C., Jaquemin, A., Gabszewicz, J.J., Weymark, J. (1983), On the stability of collusive price leadership. *Canadian Journal of Economics* 16, 17–25.

[12] Flåm, S.D. (2006), Balanced environmental games. *Computers and Operations Research* 33, 401–408.

[13] Godal, O., Holtsmark, B.J. (2011), Permit trading: Merely an efficiency-neutral redistribution away from climate change victims? *Scandinavian Journal of Economics* (forthcoming).

[14] Helm, C. (2003), International emissions trading with endogenous allowance choices. *Journal of Public Economics* 87, 2737–2747.

[15] Holtsmark, B., Sommervoll, D.E. (2008), Welfare-implications of emissions trading when endowments are endogenous. Discussion Paper 542, Statistics Norway, Oslo, Norway.

[16] Manne, A., Richels, R. (1992), Buying greenhouse insurance: The economic costs of CO_2 emission limits. MIT Press: Cambridge.

[17] Manne, A., Richels, R. (2004), US rejection of the Kyoto Protocol: The impact on compliance costs and CO_2 emissions. *Energy Policy* 32, 447–454.

[18] McGinty, M. (2007), International environmental agreements among asymmetric nations. *Oxford Economic Papers* 59, 45–62.

[19] Nordhaus, W.D. (2008), A question of balance: Economic modeling of global warming. Yale Press: USA.

[20] Osmani, D., Tol, R. (2009), Toward farsightedly stable international environmental agreements. *Journal of Public Economic Theory* 11, 455–492.

[21] Sáiz, M.E., Hendrix, E.M.T., Olieman, N.J. (2006), On the computation of stability in multiple coalition formation games. *Computational Economics* 28, 251–275.

[22] Springer, U. (2003), The market for tradable GHG permits under the Kyoto Protocol: A survey of model studies. *Energy Economics* 25, 527–551.

[23] Tol, R.S.J. (2005), The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties. *Energy Policy* 33, 2064–2074.

Table 1. Parameterization of the economy.

	Marginal benefit intercept, a_i	Marginal benefit slope, c_i	Business as usual emissions	Marginal damage, v'_i	Share of total damage, α_i
Units	US$/tC	US$yr/M(tC)^2	MtC/yr	US$/tC	%
USA	754	0.37	2013.6	15.1	16 %
Canada	657	3.39	193.8	1.3	1 %
Mexico	720	5.41	133.1	2.4	2 %
Europe	1026	0.92	1112.8	19.5	20 %
Japan	1042	2.89	361.1	5.7	6 %
Korea	720	5.30	135.8	1.5	2 %
Australia	657	5.67	115.9	0.9	1 %
Russia	1006	2.14	470.3	0.3	0 %
China	1328	0.92	1437.5	24.3	25 %
India	834	2.20	378.9	18.4	19 %
Brazil	720	3.65	197.4	3.6	4 %
South Africa	720	9.85	73.1	4.2	4 %
Total			6623.4	97.0	100 %

Table 2. Emissions and payoffs in no-trade non-cooperative Nash, and Pareto optimality.

	Nash emissions reductions	Pareto emissions reductions	Pareto less Nash emissions reductions	Nash equilibrium payoff	Pareto efficient payoffs	Pareto improvement payoffs over Nash
Units	%	%	MtC/yr	BUS$/yr	BUS$/yr	BUS$/yr
USA	2.0 %	12.9 %	219	-99	-102	-3.0
Canada	0.2 %	14.8 %	28	-8	-9	-0.6
Mexico	0.3 %	13.5 %	17	-16	-15	0.6
Europe	1.9 %	9.5 %	84	-127	-120	7.0
Japan	0.5 %	9.3 %	32	-37	-35	1.8
Korea	0.2 %	13.5 %	18	-10	-10	0.0
Australia	0.1 %	14.8 %	17	-6	-6	-0.3
Russia	0.0 %	9.6 %	45	-2	-4	-2.0
China	1.8 %	7.3 %	79	-159	-149	10.1
India	2.2 %	11.6 %	36	-120	-111	9.1
Brazil	0.5 %	13.5 %	26	-23	-23	0.9
South Africa	0.6 %	13.5 %	9	-27	-25	2.1
Total	1.5 %	10.7 %	610	-634	-608	25.6

Figure 1. Climate agreements with non-cooperative trade. All coalitions.

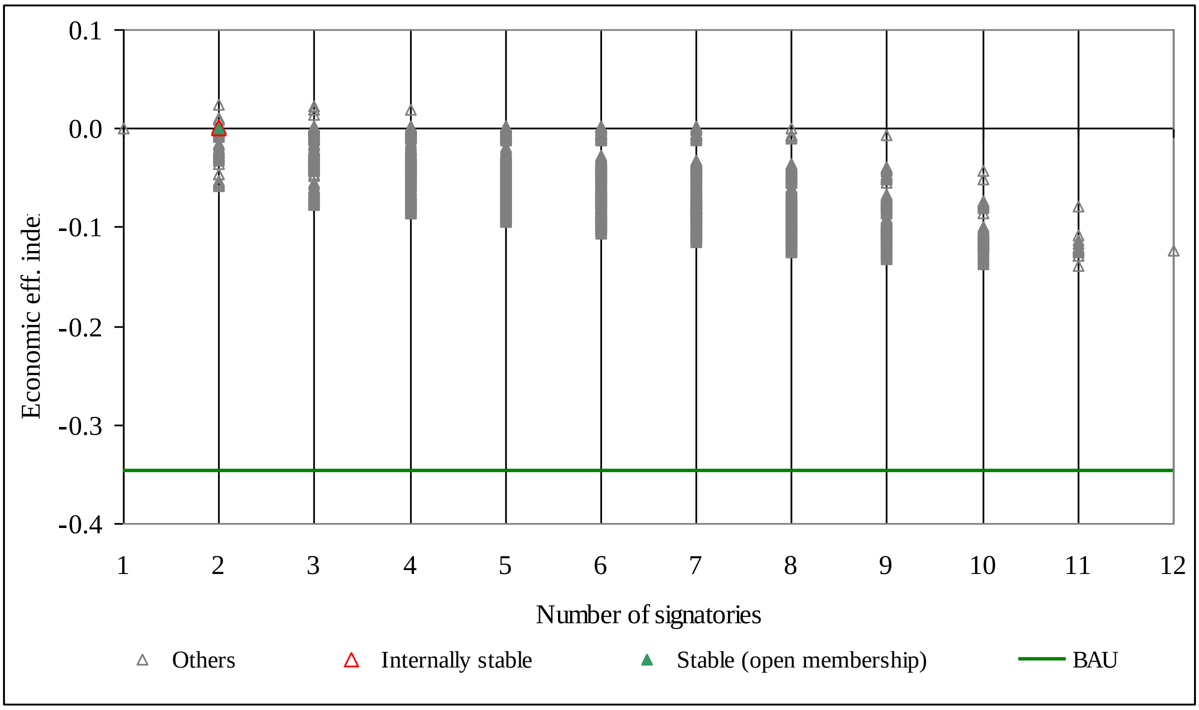

Table 3. Climate agreements with non-cooperative trade. Selected coalitions.

	Permit price (USD/tC)	Environmental index	Efficiency index	Internal stability	External stability		
					open	unanimity	majority
Noncooperative equilibrium		0.000	0.000	√			
Can–SA	2.71	0.000	0.001	√		√	√
Rus–Mex	1.36	0.000	0.001	√		√	√
Rus–Kor	0.89	0.000	0.001	√		√	√
Rus–Aus	0.59	0.000	0.000	√	√	√	√
Rus–Bra	1.94	0.001	0.001	√		√	√
Rus–SA	2.22	0.001	0.003	√		√	√
US–Eur–Chi	19.63	0.012	0.023			√	√
US–Can–Jap–Aus–Rus–Chi	7.92	-0.048	-0.093			√	√
US–Can–Mex–Kor–Aus–Rus–Chi	6.54	-0.057	-0.112			√	
Grand coalition	8.08	-0.068	-0.131		√	√	√

Figure 2. Climate agreements as a cartel with side payments. All coalitions.

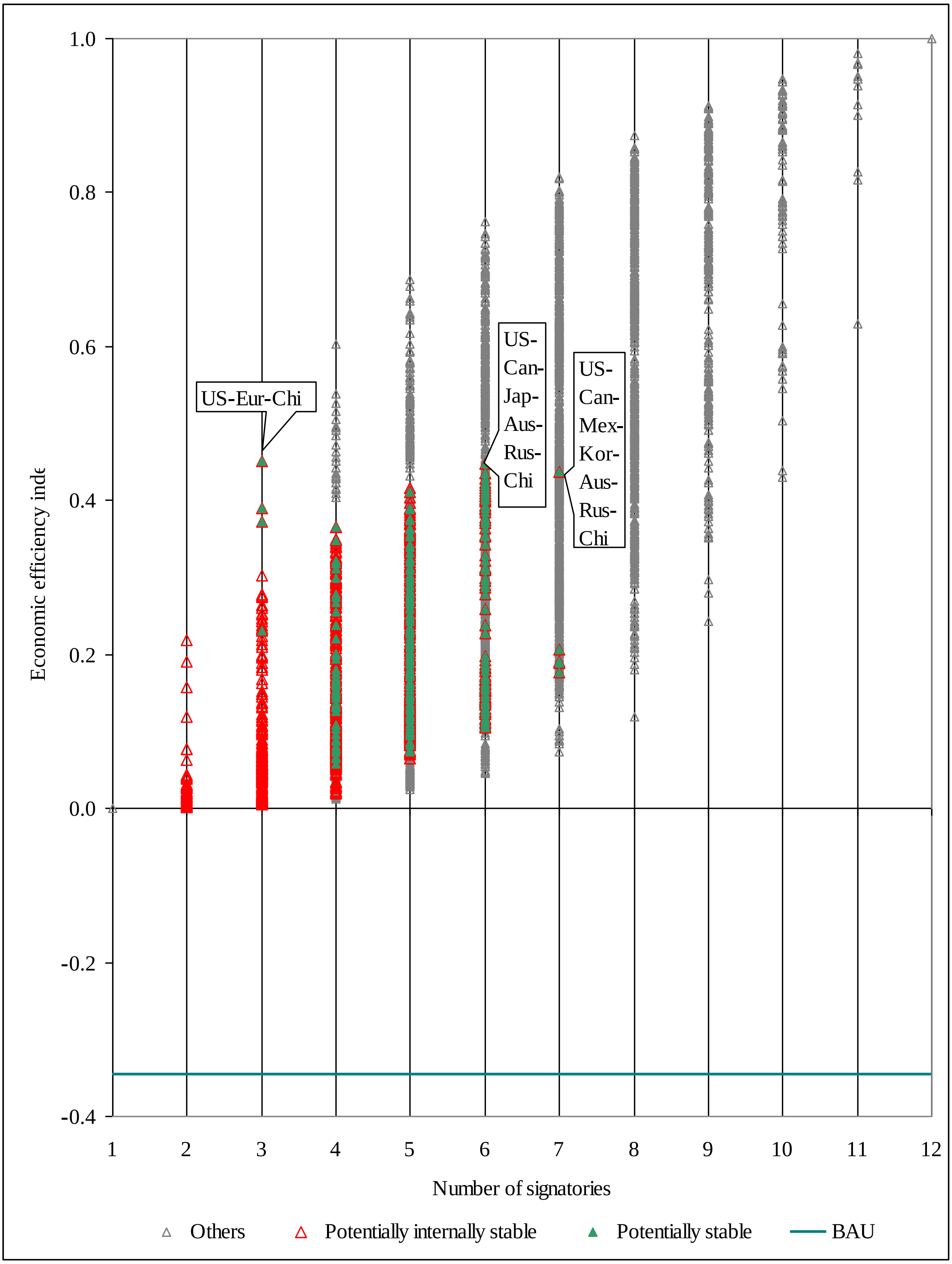

Table 4. Climate agreements as a cartel with side payments. Selected coalitions.

	Permit price (USD/tC)	Environmental index	Efficiency index	Pot. int. stability	External stability		
					open	unanimity	majority
Noncooperative equilibrium		0.000	0.000	√			
Can–SA	5.42	0.002	0.005	√			
Rus–Mex	2.71	0.002	0.004	√			
Rus–Kor	1.78	0.001	0.003	√			
Rus–Aus	1.17	0.001	0.002	√			
Rus–Bra	3.88	0.003	0.007	√			
Rus–SA	4.44	0.003	0.007	√			
US–Eur–Chi	58.88	0.323	0.452	√	√	√	√
US–Can–Jap–Aus–Rus–Chi	47.54	0.279	0.447	√	√	√	√
US–Can–Mex–Kor–Aus–Rus–Chi	45.77	0.269	0.438	√	√	√	√
Grand coalition	97.00	1.000	1.000		√	√	√

Table 5. Payoffs and transfers in the gamma core.

	Payoff in the gamma core	Core payoff less Nash	Transfers in core	Permit exports	Initial quota allowance
Units	BUS$/yr	BUS$/yr	BUS$/yr	MtC/yr	%
USA	-94.8	4.0	7.0	72.5	9.3 %
Canada	-7.9	0.3	1.0	9.8	9.7 %
Mexico	-15.1	0.6	0.0	0.3	13.2 %
Europe	-121.9	5.1	-1.8	-18.9	11.1 %
Japan	-35.5	1.5	-0.3	-3.5	10.3 %
Korea	-9.3	0.4	0.4	3.8	10.7 %
Australia	-5.5	0.2	0.5	5.4	10.1 %
Russia	-1.8	0.1	2.1	21.6	5.0 %
China	-152.6	6.4	-3.6	-37.5	9.9 %
India	-115.0	4.8	-4.3	-44.2	23.3 %
Brazil	-22.5	0.9	0.0	0.5	13.2 %
South Africa	-26.0	1.1	-1.0	-9.9	27.0 %
Total	-608.0	25.6	0.0	0.0	10.7 %