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PERMIT TRADING AND STABILITY OF INTERNATIONAL CLIMATE AGREEMENTS

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We analyze the implication of different allocation schemes of CO_2-emission permits for stability and the success of international climate agreements. Our model combines a game theoretical with an empirical module that comprises 12 world regions and captures important dynamic aspects of the climate change problem. We consider seven different permit allocation schemes. Two "pragmatic schemes" allocate permits according to a uniform emission reduction quota, five "equitable schemes" allocate permits based on some normative criteria frequently discussed in the literature permit trading can raise participation and the success of climate agreements, but pragmatic schemes are superior to equitable ones.

JEL classification codes: C72, Q25, Q28
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I. Introduction

Emission permits have been proposed as an efficient instrument to tackle both national and international environmental problems. Recently, this market-based

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instrument has gained increasing attention in the context of the Kyoto Protocol, aiming at controlling global warming. Since greenhouse gas emission affects all countries, it can be expected that a sufficient high participation in permit trading will guarantee a well-functioning market. However, there has been much debate about the distributional effects of different permit allocation schemes. Rose et al. (1998) took a prominent lead in this discussion, classifying different allocation schemes, clarifying their motivation and analyzing their impact on different countries. The discussion initiated many other papers (e.g., Kverndokk 1995 and Böhringer et al. 2002) dealing with various notions of fair allocations of permits. It is recognized that not only efficiency but also fairness aspects may play an important role for the participation and success of a global warming treaty. However, this literature only studies the impact of different allocation schemes on net abatement costs of individual participants (abatement costs plus/minus the outlay/receipt from permit trading). Hence, not much can be concluded about whether and which countries have an incentive to join an international environmental agreement (IEA) and whether such a treaty will be self-enforcing. In order to analyze participation and stability, two more steps are necessary.

First, not only abatement costs but also benefits from joint abatement policies have to be taken in consideration. Only this gives a complete picture of the basic incentives to participate in an agreement. That is, we can test whether cooperation is not only globally but also individually rational. We call a treaty individually rational if each participant receives a net benefit exceeding that in the non-cooperative status quo. As shown for instance in Eyckmans et al. (1994) and Germain and van Steenberghe (2003), not all permit allocation schemes that are deemed to be fair guarantee individual rationality to all participants. For instance, a permit allocation based on per capita may appear to be fair (“one-man-one vote”), but leads to very large transfers from industrialized to developing countries that may violate the interests of donors.

Second, even though individual rationality may be seen as a necessary condition for cooperation, it is by no means a sufficient condition. Since abatement constitutes a public good, countries may be better off not participating in an individually rational IEA, saving abatement costs and benefiting from the efforts of signatories. Consequently, in view of the fact that there is no supranational institution that can enforce a global treaty, IEAs must also be self-enforcing. We check this with the concept of internal and external stability which has been widely applied in the game theoretical literature on IEAs (e.g., Barrett 1994 and Carraro and Siniscalco 1993).[1] Different from this literature, however, we combine our game theoretical

[1] For an overview of this literature see Finus (2003).

analysis with an empirical model that captures twelve world regions. That is, we neither model heterogeneity in a stylized way as for instance in Finus and Rundshagen (1998) and Hoel (1992), nor do we consider stylized transfer rules as for instance in Botteon and Carraro (1997) and Eyckmans and Tulkens (2003).

The objective of this paper is to test whether stable coalitions exist under various permit allocation schemes and if this is the case whether they improve upon the non-cooperative outcome. We consider two "pragmatic scenarios" that allocate permits according to a uniform emission reduction quota and five "equity scenarios" that allocate permits based on some normative criteria frequently discussed in the literature. Different from Bosello, Buchner and Carraro (2003), Eyckmans and Finus (2003) and Weikard, Finus and Altamirano-Cabrera (2004) that test stability of outcome-based allocation rules, we consider allocation based-rules.[2] It turns out that permit trading can improve upon the success of self-enforcing climate agreements but pragmatic are superior to equity schemes. Thus, moral motives may not always be a good guide for the design of effective and self-enforcing treaties.

In the following, we introduce the game theoretical and empirical module in Section II. We motivate our permit trading schemes and discuss some fundamental features in Section III and report about results of our stability analysis in Section IV. Section V wraps up with a summary and draws some conclusions.

II. The model

A. Game theoretical module

Coalition formation is modeled as a two-stage game. In the first stage, countries or regions ($i \in I=\{1,...,N\}$) decide on their membership strategy; in the second stage, they choose their abatement strategies. In the first stage, we assume that countries have two membership strategies: strategy $\sigma_i = 0$ means "I do not want to join the agreement" and $\sigma_i = 1$ means "I want to become a member of a climate treaty". Countries that announce $\sigma_i = 0$ form a singleton coalition and those that announce

[2] This categorization is due to Rose et al. (1998). Permits may be allocated based on some criteria aiming at influencing the initial allocation (allocation-based), the final allocation after trade has taken place (outcome-based) or important factors associated with trading (process-based). Since governments and their representatives usually bargain on the allocation of permits (though they may determine their bargaining position by conjecturing the outcome or some variables associated with the process of trading), we believe that allocation-based rules should receive sufficient attention in the analysis.

σ_i = 1 become members of a non-trivial coalition (i.e., a coalition of at least two members). Hence, a vector of announcements $\sigma = (\sigma_1, \sigma_2, \ldots, \sigma_N)$, $\sigma \in \Sigma$, leads to coalition structure c = (s, 1,..., 1), $c \in C$, with s either a non-trivial coalition if at least two countries have announced $\sigma_i = 1$ or s = {i} if either all countries have announced $\sigma_i = 0$ or only one country has announced σ_i = 1. Hence, there exist 4096 different membership vectors but "only" 4084 different coalition structures in the context of twelve players (regions).[3] If s = {i}, this is called the "singleton coalition structure" and if s = I, this is called the "grand coalition structure".

In the second stage, countries choose their abatement strategies q_i based on the following payoff function:

$$\pi_i = B_i\left(\sum_{i=1}^{N} q_i\right) - C_i(q_i), \tag{1}$$

assuming a concave benefit function from global abatement, B_i, and a convex abatement cost function from individual abatement, C_i. For a given coalition structure c, we assume that non-signatories (σ_i = 0) pursue their self-interests, maximizing π_i with respect to q_i, taking the abatement level of all other countries as given. Assuming an interior equilibrium, this leads to the following first-order condition:

$$B_i'\left(\sum_{i=1}^{N} q_i\right) = C_i'(q_i) \,\forall\, i \notin s, \tag{2}$$

where primes denote derivatives. In contrast, signatories (σ_i = 1) are assumed to maximize the aggregate welfare of their coalition. This leads to the following first order conditions:

$$\sum_{i \in s} B_i'\left(\sum_{i=1}^{N} q_i\right) = C_i'(q_i) \;\forall\, i \in s. \tag{3}$$

The simultaneous solution of the first order conditions of non-signatories and signatories leads to abatement vector $q^*(c)$. This abatement vector can be interpreted as a partial Nash equilibrium between coalition s and the singleton players (Chander and Tulkens 1997). Hence, in equilibrium, $C_i'(q_i^*) = C_j'(q_j^*)$ for all i and j that belong to s. That is, the abatement vector of the coalition is efficient for the coalition. Of course, this does not extend to outsiders. Consequently, the grand coalition

[3] This should not be confused as meaning that the mapping of membership strategies into coalition structures would not be unique.

structure (s = I), representing full cooperation, chooses a globally optimal abatement vector and the singleton coalition structure (s={i}), representing no cooperation, corresponds to the "classical" Nash equilibrium. Any other coalition structure may be seen as partial cooperation.

If $q^*(c)$ is unique for all $c \in C$, then the payoff vector $\pi(q^*(c))$ with $\pi_i(q^*(c)) = B_i(\sum_{i=1}^{N} q_i^*(c)) - C_i(q_i^*(c))$ is unique in the second stage. In section II.C, we will argue that this is indeed the case and that $q^*(c)$ lies in the interior of the abatement space. At this stage, it suffices to notice that $\pi(q^*(c))$ represents the case without permit trading. In the case of permit trading, payoffs have to be modified. For simplicity, we assume that permits are only traded among cooperating countries, i.e., among coalition members (see section V for a discussion of this assumption). Hence, a coalition member's payoff can be written as

$$\tilde{\pi}_i(q^*(c), \bar{q}_i(t)) = \pi_i(q^*(c)) - p \cdot (\bar{q}_i(t) - q_i^*(c)), \quad (4)$$

where p is the permit price and $\bar{q}_i(t)$ is the assigned abatement resulting from some allocation under a particular permit trading system $t \in T$. The second term on the right hand side of equation (4) is positive if a country is a permit seller ($\bar{q}_i(t) < q_i^*(c)$) and negative if a country is a permit buyer ($\bar{q}_i(t) > q_i^*(c)$). The price of permits is equal to marginal abatement costs in equilibrium and follows immediately from the first order conditions of signatories in (3). Thus, the "final" payoff $\tilde{\pi}_i$ in (4) can be interpreted as the payoff from cooperation without transfers, π_i, plus or minus a transfer that depends on the allocation of abatement, $\bar{q}_i(t)$. In section IV, we will discuss various permit schemes that determine $\bar{q}_i(t)$. At this stage, it suffices to notice that because $\pi(q^*(c))$ is unique also $\tilde{\pi}_i(q^*(c), \bar{q}_i(t))$ is unique for each coalition structure $c \in C$ and any permit scheme $t \in T$.

Taken together, payoffs to country i depend on the coalition structure $c \in C$ determined in the first stage of the game and on abatement strategies $q \in Q$ and the permit trading systems $t \in T$ chosen in the second stage of the game, $\pi_i(c, q, t)$. Since abatement q follows from the assumption of joint welfare maximization of coalition members and the allocation of permits follows from the assumption about a particular permit trading system, we can thus define stability of coalition structure c as follows:

Stable Coalition Structures. *Coalition structure $c \in C$ resulting from announcement $\sigma \in \Sigma$ is called stable if for all $i \in I$, $\sigma_i^* \neq \sigma_i'$: $\pi_i(\sigma_i^*, \sigma_{-i}^*) \geq \pi_i(\sigma_i', \sigma_{-i}^*)$ assuming some permit trading scheme $t \in T$ and that $q \in Q$ follows from the assumption of joint welfare maximization of coalition members.*

Obviously, our definition implies that a coalition structure is called stable if membership strategies constitute a Nash equilibrium. This definition is similar to the concept of internal and external stability: in equilibrium, no signatory has an incentive to leave the coalition by changing its announcement from $\sigma_i^* = 1$ to $\sigma_i' = 0$ (internal stability) and no non-signatory has an incentive to join the coalition by announcing $\sigma_i' = 1$ instead of $\sigma_i^* = 0$ (external stability). The advantage of our definition is that existence of an equilibrium is guaranteed. The reason is that the singleton coalition structure can always be supported as a Nash equilibrium: suppose all countries announce $\sigma_i = 0$, then no single country can change this coalition structure by unilaterally changing its membership strategy. The advantage of the other definition is that it allows separating stability into two dimensions. Hence, when discussing stability in the following, we distinguish between internal and external stability.

It is evident that the definition of stable coalition structures implies voluntary participation since signatories can leave their coalition if they find it more attractive to free-ride and non-signatories can join the agreement if this pays.

B. Empirical module

In this section, we explain our empirical module - called STACO-model. Since the model has been laid out in much detail in Finus, Altamirano-Cabrera and van Ierland (2004), we briefly describe here only its main features. The main idea of STACO is to calibrate the following payoff function:

$$\pi_i(q) = \sum_{t=1}^{T} (1 + r_i)^{-t} (B_{it}(q_t) - C_{it}(q_{it})), \tag{5}$$

where the philosophy behind the model comprises three items. First, the model should reflect important dynamics of climate models. Therefore, STACO considers a period of 100 years, starting in 2010 and bases its calibration on the widely known DICE-model of Nordhaus (1994) for the development of global emissions and concentration. Second, in order to make the model interesting for a game theoretical analysis, there should be a sufficient number of different players. Therefore, STACO uses abatement cost estimates of Ellerman and Decaux (1998) for twelve world regions. For global benefits and regional benefits from abatement (in the form of reduced damages), STACO uses estimates of Fankhauser (1995) and Tol (1997).

Third, the model must be simple enough to be tractable for a game theoretical analysis. Therefore, STACO assumes stationary abatement strategies, fits the parameters to this specification, leading to the following discounted payoff function:

$$\pi_i(q) = \gamma_i \mu_B \delta_b \sum_{i=1}^{N} q_i - \delta_c \left[\tfrac{1}{3} \cdot \alpha_i \cdot q_i^{\,3} + \tfrac{1}{2} \cdot \beta_i \cdot q_i^{\,2} \right], \qquad (6)$$

where q_i is the total abatement over 100 years, $q_i = \sum_{t=1}^{100} q_{it}$. The global benefit parameter is μ_B, the regional benefit parameter is γ_i, representing the shares of the different world regions in global benefits, $0 \le \gamma_i \le 1$, $\sum_{i=1}^{N} \gamma_i = 1$ and α_i and β_i are regional abatement cost parameters. The parameters δ_b and δ_c capture discounting in STACO; in the case of δ_b it further includes the decay of greenhouse gases. In our "standard case" we assume a discount rate of 2 percent.[4] Note that μ_B δ_b represents global marginal benefits. It turns out that μ_B δ_b=37.4 US$ per ton of carbon, a figure that is much in line with other studies (e.g., Plambeck and Hope 1996). The regional parameters reflect differences of twelve world regions: USA, Japan (JPN), European Union (EU-15), other OECD countries (O-OECD), Eastern European countries (EE), former Soviet Union (FSU), energy exporting countries (EEX), China, India, dynamic Asian economies (DAE), Brazil and "rest of the world" (ROW). We use the abbreviations in brackets in the following.[5] The parameters are listed in the Appendix in Table A.1 and their implications are visualized in Figure 1 and 2 below.

Figure 1 lists regions in descending order of regional benefit shares. It is evident that the large industrialized regions are the main beneficiaries of global abatement whereas EEX, DAE and Brazil receive the smallest share of global benefits.

From Figure 2, it is evident that marginal abatement costs never intersect. Moreover, marginal abatement costs vary widely: China and USA have the flattest curves whereas Brazil as well as Japan have the steepest. Roughly speaking, those regions with low initial emissions (e.g., Brazil and Japan) face steep marginal abatement cost curves (see Table A.1 in the Appendix) since cheap abatement options have already been exploited and substitution to more effective abatement technologies is expensive. For regions with high initial emissions (e.g., China and USA) just the opposite holds.

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[4] For a discount rate of 2 percent, δ_b=1385 and δ_c=43.1 in STACO. The parameter μ_B represents damages in terms of a loss of GDP for a doubling of greenhouse gas concentration, expressed in percentages. We take μ_B = 0.027 (meaning a 2.7 percent loss) from Tol (1997). In section 4, these assumptions will be subject to a comprehensive sensitivity analysis.

[5] EU-15 comprises the 15 countries of the European Union as of 1995. O-OECD includes among other countries Canada, Australia and New Zealand. EE includes for instance Hungary, Poland, and Czech Republic. EEX includes for example the Middle East Countries, Mexico, Venezuela and Indonesia. DAE comprises South Korea, Philippines, Thailand and Singapore. ROW includes for instance South Africa, Morocco and many countries in Latin America and Asia.

Figure 1. Regional benefits from global abatement

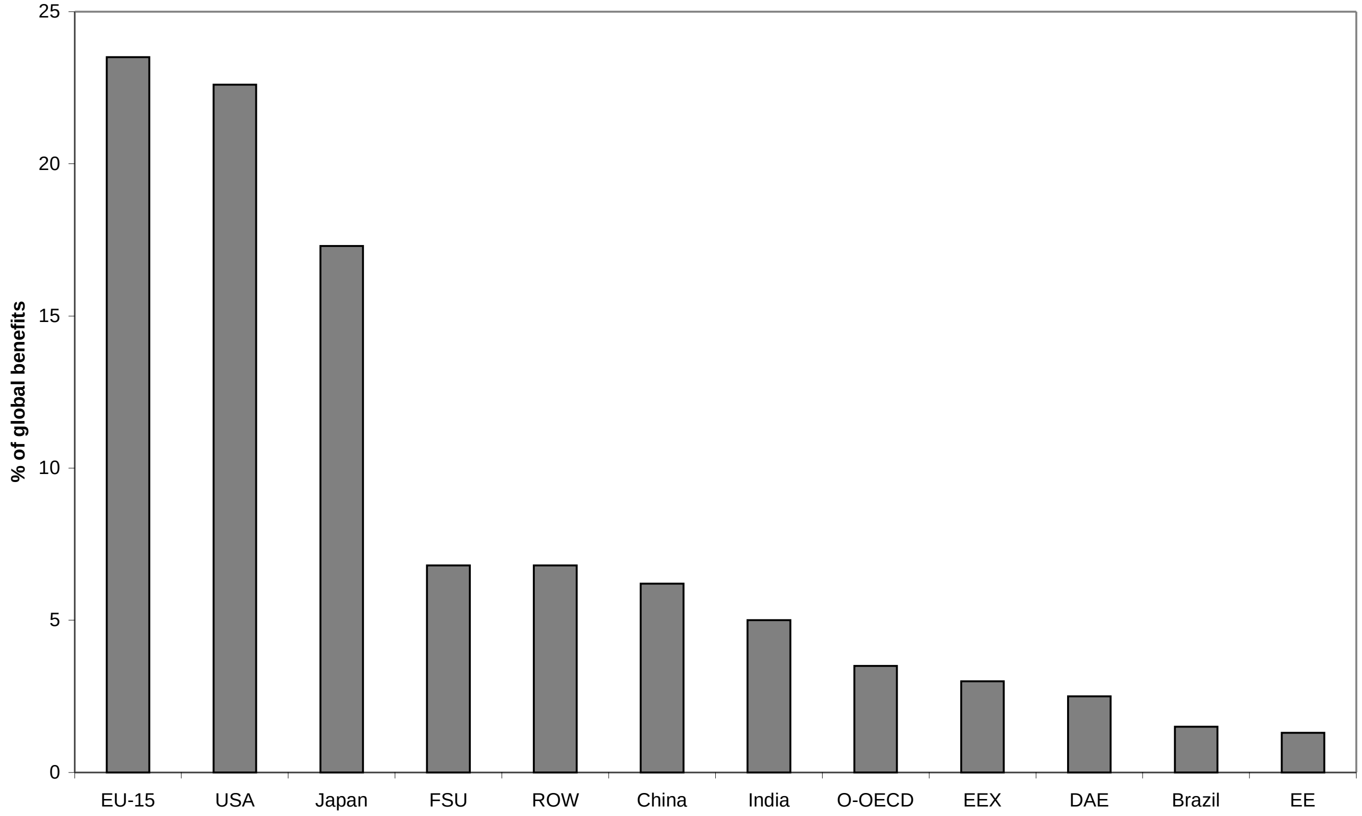
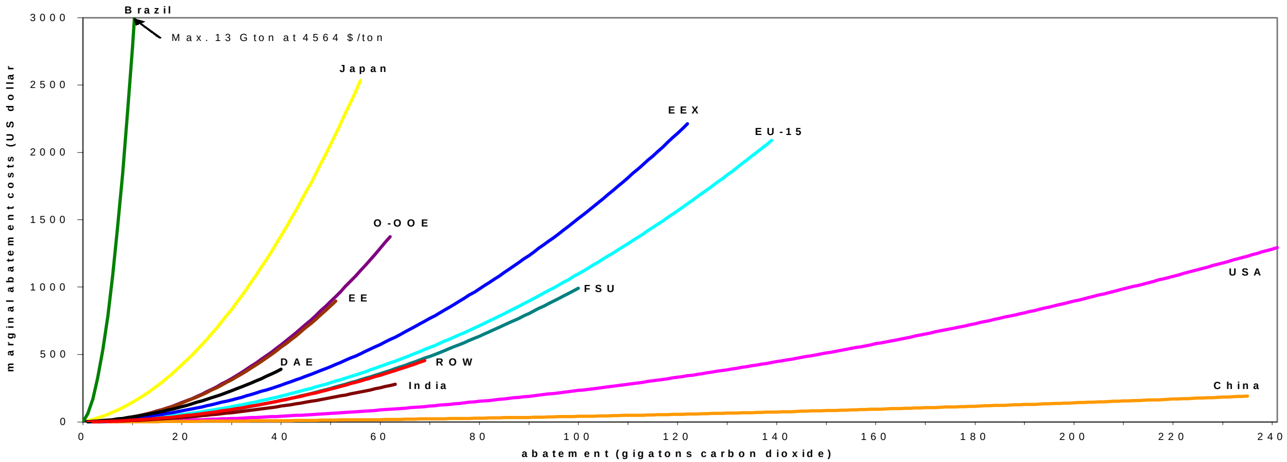


Figure 2. Marginal abatement cost functions



C. General features of the model

In this section, we discuss some general features of our model, relating to the game theoretical and the empirical module.

First, in section II.A, we pointed out that a unique abatement vector for each coalition $c \in C$ guarantees a unique payoff vector. Considering the empirical specification of the payoff function (see equation (6)), it is evident that regions have a dominant strategy because the first order conditions of signatories are $\mu_B \delta_b \sum_{i \in s} \gamma_i = \delta_c (\alpha_i \cdot q_i{}^2 + \beta_i \cdot q_i)$ and those of non-signatories are $\mu_B \delta_b \gamma_i = \delta_c (\alpha_i \cdot q_i{}^2 + \beta_i \cdot q_i)$. Thus, uniqueness is evident. An interior solution follows from two pieces of information. a) $C_i'(q_i)$ is an increasing function, $C_i'(q_i = 0) = 0$ and $\sum_{i \in s} B_i' = \mu_B \delta_b \sum_{i \in s} \gamma_i \geq B_i' = \mu_B \delta_b \gamma_i > 0$, hence $q_i^* > 0 \ \forall i \in I$ and for any coalition structure. Notice that this implies that even in the singleton coalition structure, corresponding to the "classical" Nash equilibrium, some abatement is undertaken compared to the business-as-usual scenario, and hence $e_i^{BAU} > e_i^{Nash} \ \forall i \in I$, where e_i^{BAU} is defined as emission level in the business-as-usual scenario and e_i^{Nash} as emission level in the Nash equilibrium. b) Generally, we can choose a sufficient high upper bound q_i^{max} to guarantee an interior solution. However, in our model abatement means to reduce emissions from the business-as-usual emission level, e_i^{BAU}. Hence, it seems sensible to require $q_i^{max} \leq e_i^{BAU}$. Since it follows from $\mu_B \delta_b \sum_{i \in s} \gamma_i = \delta_c (\alpha_i \cdot q_i{}^2 + \beta_i \cdot q_i)$ that q_i^* takes on the largest value if s=I (corresponding to the "classical" global optimum), we only have to check whether $q_i^*(s = I) \leq e_i^{BAU}$ holds for all $i \in I$. In our model, it turns out that this is indeed the case.

Second, in our model, superadditivity holds. That is, whenever a country j joins coalition s, so that coalition structure changes from c to $\tilde{c}$, aggregate welfare of countries $s \cup \{j\}$ increases, $\sum_{i \in s} \pi_i(c, t) + \pi_j(c) < \sum_{i \in s \cup \{j\}} \pi_i(\tilde{c}, t)$. The reason is simple. First, the aggregate payoff to coalition s and $s \cup \{j\}$ is not affected by the kind of permit trading scheme: permit trading only affects individual payoffs of coalition members through transfers but transfers add up to zero. (Recall that non-signatories are not involved in trading.) Second, outsiders $I \setminus \{s \cup \{j\}\}$ have a dominant strategy. Hence, they will not change their abatement level in $\tilde{c}$ compared to c. Hence, if we let q^s, $q^{s \cup \{j\}}$ and q_j denote the abatement vector of signatories before and after country j joined coalition s and abatement of country j, respectively, then $\max_{q^s} \sum_{i \in s} \pi_i + \max_{q_j} \pi_j < \max_{q^{s \cup \{j\}}} \sum_{i \in s \cup \{j\}} \pi_i$ must hold.

Third, in our model, cooperation generates positive externalities. That is, whenever a country j joins coalition s, so that coalition structure c changes to $\tilde{c}$, outsiders $k \notin s \cup \{j\}$ gain $\pi_k(c) < \pi_k(\tilde{c})$. From the first order conditions of signatories, it is evident that abatement of each member increases because the sum of marginal benefits increases from $\mu_B \delta_B \sum_{i \in s} \gamma_i$ to $\mu_B \delta_B \sum_{i \in s \cup \{j\}} \gamma_i$. Hence, global abatement increases, outsiders´ benefits increase from c to $\tilde{c}$ but their abatement costs remain the same.

Fourth, superadditivity together with positive externalities imply that global welfare is raised if participation is gradually increased. Nevertheless, membership matters. That is, global welfare may well be different in two coalitions s_1 and s_2 that are of the same size but comprise different members.

Fifth, in the Introduction we mentioned that an agreement must be individually rational and self-enforcing to be stable. Evidently, we check the self-enforcing part through Definition 1 of stable coalition structures. Less evident is that this automatically implies to check also for individual rationality. The reason is that internal stability implies individual rationality (but not vice versa). Suppose coalition s is not individually rational for member i, then member i can leave the agreement and because of the positive externality property (see item 3 above), he will be (strictly) better off than in the singleton coalition structure (provide $s \backslash \{i\}$ comprises at least two members).

Sixth, generally, the advantage of participating in a coalition is that this increases global abatement. Moreover, own abatement efforts are matched by others. This increases benefits from global abatement but also increases abatement costs. The relative size of both effects determines whether it pays to join a coalition. As a tendency, the higher participation in an agreement, the less attractive it becomes to join a coalition and the more attractive it becomes to leave a coalition due to the strict concavity of the payoff function. Therefore, stable coalitions are usually only small.

Seventh, participation in a stable agreement will also depend on membership and on the permit trading system. Since countries have different benefit and cost functions, joint welfare maximization may imply a very asymmetric distribution of the gains from cooperation. For instance, a coalition member, say i, with a flat marginal abatement cost function will have to contribute more to abatement than a member, say j, with a steep marginal abatement cost function. If i has also lower marginal benefits than j, then i may well be worse off from cooperation or at least receives a low payoff. Consequently, it may pay country i to free-ride. This may be different if country i receives a transfer from country j which may be accomplished via a permit trading system that allocates a sufficient amount of permits to country i. In our model, a region i is for instance EE, DAE, China and India and a region j for instance EU-15 and Japan.

III. Fundamentals about permit trading

A. Motivation of permit schemes

In section II.A, we observed that payoffs in a coalition structure c are affected by the global abatement level $\sum_{i=1}^{N} q_i^*(c)$ and the individual abatement level $q_i^*(c)$, $\pi_i = B_i(\sum_{i=1}^{N} q_i^*(c)) - C_i(q_i^*(c))$. This holds for non-signatories. For signatories, payoffs also depend on the assigned abatement level $\bar{q}_i(t)$ that follows from the allocation of permits under some permit scheme t, $\tilde{\pi}_i = \pi_i - p \cdot (\bar{q}_i(t) - q_i^*(c))$. Noting that emission permits of region i, $\bar{e}_i$, mean to allocate a fraction $0 \leq \lambda_i \leq 1$ of the total amount of permits $\sum_{i \in s} \bar{e}_i$, to each member i, $\bar{e}_i = \lambda_i \sum_{i \in s} \bar{e}_i$, $\sum_{i \in s} \lambda_i = 1$, and recalling that abatement is defined as $q_i = e_i^{BAU} - e_i$ in our model, $\sum_{i \in s} \bar{e}_i = \sum_{i \in s} e_i^*$ with $\sum_{i \in s} e_i^* = \sum_{i \in s} e_i^{BAU} - \sum_{i \in s} q_i^*$, then the allocation of abatement can be expressed as follows:

$$\bar{q}_i(t) = e_i^{BAU} - \lambda_i \left(\sum_{i \in s} e_i^{BAU} - \sum_{i \in s} q_i^*(c) \right). \tag{7}$$

Thus, different permit schemes $t \in T$ can be related to different weights λ_i. In the literature, several schemes have been proposed of which we consider seven in this paper. We only briefly comment on these schemes and refer the reader to a more extensive discussion of their motivation to Cazorla and Toman (2000) and Rose et al. (1998). The first two schemes are called “pragmatic schemes”, the next five are called “equitable schemes”. The names that we attach to each scheme are shown in the first row and the mathematical specifications of weights are displayed in the second row in Table 1. For the grand coalition, weights (expressed as percentage) are displayed for each region in the subsequent rows. This gives a first idea of the relative impact of different schemes in terms of weights, though it has to be pointed out that weights are different in other coalition structures. The base data for computations of weights is provided in the Appendix, Table A.2.

Pragmatic schemes

Our pragmatic schemes belong to so-called sovereignty rules because they do not much interfere with the status quo. Both schemes assume that all members receive emission permits that represent the same percentage from some base emission level. This implies to allocate uniform emission reduction quotas to each member. Such a scheme has been applied in the Helsinki Protocol on Sulfur Reduction in Europe and in many other IEAs. However, different from these treaties,

Table 1. Permit schemes and shares in the grand coalition

Regions	Pragmatic schemes		Equitable schemes				
	Quota BAU (1)	Quota Nash (2)	Egalitarian (3)	Historical responsibility (4)	Ability to pay (5)	Ability to pollute (6)	Energy efficiency (7)
	$\frac{e_i^{BAU}}{\sum_{i \in s} e_i^{BAU}}$	$\frac{e_i^{Nash}}{\sum_{i \in s} e_i^{Nash}}$	$\frac{Pop_i}{\sum_{i \in s} Pop_i}$	$\frac{(e_i^{BAU})^{-1}}{\sum_{i \in s} (e_i^{BAU})^{-1}}$	$\frac{(GDP_i/Pop_i)^{-1}}{\sum_{i \in s} (GDP_i/Pop_i)^{-1}}$	$\frac{(e_i^{BAU}/Pop_i)^{-1}}{\sum_{i \in s} (e_i^{BAU}/Pop_i)^{-1}}$	$\frac{(e_i^{BAU}/GDP_i)^{-1}}{\sum_{i \in s} (e_i^{BAU}/GDP_i)^{-1}}$
USA	20.2	19.8	4.8	1.9	0.5	1.6	9.8
Japan	4.7	4.8	1.9	8.2	0.3	2.8	26.8
EU-15	11.7	11.7	5.8	3.3	0.6	3.4	18.4
O-OECD	5.2	5.3	2.2	7.4	1.1	2.9	8.2
EE	4.3	4.5	1.9	9.0	4.4	3.0	2.1
FSU	8.4	8.3	4.5	4.6	8.2	3.6	1.3
EEX	10.2	10.6	24.9	3.7	14.8	16.7	3.6
China	19.7	19.4	20.9	1.9	18.5	7.2	1.2
India	5.3	5.4	17.8	7.3	37.0	23.1	2.0
DAE	3.4	3.5	3.2	11.1	3.2	6.4	6.4
Brazil	1.1	1.1	3.0	35.2	3.6	18.6	16.0
ROW	5.9	5.8	9.1	6.5	7.8	10.6	4.3
Total	100	100	100	100	100	100	100

Notes: All figures are expressed as a percentage. e_i^{BAU} = emissions in the BAU scenario for country i; e_i^{Nash} = emissions in the Nash equilibrium for country i; Pop_i = level of population in country i; GDP_i = level of GDP in country i.

in our model such quotas can be traded as intended under the Kyoto Protocol. "Quota BAU" (scheme 1) assumes base emissions in the business-as-usual scenario, e_i^{BAU}; "Quota Nash" (scheme 2) assumes base emissions in the classical Nash equilibrium, e_i^{Nash}, corresponding to those in the singleton coalition structure. Both emission levels may be interpreted as the status quo before an agreement is signed. The alternative assumptions allow us to check whether our results are sensitive to the choice of the base-line emission level.

From Table 1, we observe that weights between scenario 1 and 2 differ only slightly. This is because the Nash equilibrium implies only a minor emission reduction from BAU-emissions (see Table A.2 in the Appendix). Since base line emissions are strongly concentrated in USA and China, those regions receive the highest weights. We now turn to our "equitable schemes".

Equitable schemes

"Egalitarian" (scheme 3) allocates emission permits on a per capita basis. This rule acknowledges that all men should have the same right to emit: "one man one vote". Evidently, energy exporting countries (EEX), China and India, receive the highest shares in the grand coalition since a large portion of total population lives in these regions.

"Historical responsibility" (scheme 4) allocates permits inversely to BAU-emissions because those countries that have contributed to current greenhouse gas concentration should contribute more to mitigate this problem. Thus, weights under this scheme are the mirror image of "Quota BAU", and therefore Brazil and dynamic Asian economies (DAE) receive high weights.

"Ability to pay" (scheme 5) allocates permits inversely to welfare levels measured as gross domestic product (GDP). This rule argues that wealthier nations should take on more responsibility in global climate change control than poorer nations. However, this rule may also be seen as a vehicle of development aid through environmental policy by allocating more permits to poorer nations. Again, those regions that receive high shares of emission permits are those mentioned under the "Egalitarian scheme" and are mainly developing countries.

The scheme "Ability to pollute" (scheme 6) is similar in spirit to "Historical responsibility", except that weights are not based on emissions but on emissions per capita. It has also some connection to "Egalitarian" where weights are based on population. Thus, this scheme may be defended by arguing that every man has the same responsibility for preserving the climate system. Since the USA has the highest emission per capita ratio, they receive the lowest weight. In contrast, due to low current emissions and high population density, developing countries receive high weights under this scheme.

"Energy efficiency" (scheme 7) allocates emission permits inversely to the emission/GDP ratio. It therefore rewards regions with "advanced environmental technology" like Japan and European Union (EU-15) but gives low weights to China, India and Eastern European countries (EE) that have "dirty industries".

B. Illustration of permit schemes: Some fundamental relations

In this subsection, we illustrate some of the implications of the seven different permit trading schemes in Table 2. As a reference point, we also display the base case of no permit trading. Again, we choose the grand coalition to illustrate some fundamental relations. For each scenario, the gains from cooperation are measured in relation to the singleton coalition structure, corresponding to the classical Nash equilibrium. Since the payoff to a region can be interpreted as its payoff without trading plus or minus a transfer (see section II.A), we also display transfers as implied by the various permit schemes. A positive number means to pay a transfer (permit buyer) and a negative number means to receive a transfer (permit seller). In order to gain some insights about the dimension of trading, we also display total transfers, that is, the sum of all positive or negative numbers. Moreover, in order to get an idea about the distribution of the gains from cooperation, we compute the standard deviation of the gains from cooperation.

From Table 2 the following observations are interesting:

First, the total gain from cooperation in the social optimum is with 4,071 billion US$ large given the fact that the global payoff in the Nash equilibrium is only 1,960 billion US$.

Second, the standard deviation of the gains from cooperation is generally large. However, there are significant differences: The two pragmatic schemes show the lowest standard deviation and some of the equitable schemes have a very high standard deviation, exceeding that without permit trading to a large extent. The large spread of the gains also shows up in large transfers implied by the various permit trading schemes. Obviously, the equity schemes imply a major reshuffle of the gains from cooperation through permit trading, but most of them replace the asymmetry without trading through another asymmetry that is even larger.

Third, neither the base case of no permit trading nor any of the permit schemes implies that cooperation is profitable for all participants. There are always at least two regions that are worse off than in the Nash equilibrium. For the equity schemes, individual rationality is sometimes severely violated for almost half of all regions.

Table 2. Gains and transactions under various permit schemes: Grand coalition

Regions	No permit trading		Pragmatic schemes				Equitable schemes									
			Quota BAU (1)		Quota Nash (2)		Egalitarian (3)		Historical responsibility (4)		Ability to pay (5)		Ability to pollute (6)		Energy intensity (7)	
	Gains	Trans-Fers	Gains	Trans-fers	Gains	Trans-fers	Gains	Trans-fers	Gains	Trans-fers	Gains	Trans-fers	Gains	Trans-fers	Gains	Trans-fers
USA	1,241	-	721	520	577	664	-4,709	5,950	-5,716	6,957	-6,200	7,441	-5,815	7,056	-2,941	4,182
Japan	1,236	-	926	310	976	260	-30	1,266	2,160	-923	-596	1,832	286	950	8,703	-7,467
EU-15	1,569	-	1,051	518	1,037	531	-1,006	2,574	-1,917	3,486	-2,857	4,426	-1,862	3,430	3,370	-1,801
O-OECD	133	-	17	115	45	87	-1,029	1,162	767	-634	-1,421	1,554	-785	918	1,068	-936
EE	-33	-	-68	35	-24	-9	-936	904	1,487	-1,520	-63	31	-561	528	-860	827
FSU	269	-	189	81	179	90	-1,190	1,460	-1,165	1,434	196	74	-1,483	1,752	-2,289	2,559
EEX	38	-	-475	513	-330	368	4,710	-4,672	-2,746	2,784	959	-922	1,811	-1,773	-2,786	2,824
China	-866	-	820	-1,686	698	-1,564	1,233	-2,099	-5,424	4,558	679	-1,545	-3,563	2,696	-5,696	4,830
India	83	-	378	-295	378	-294	4,765	-4,682	1,002	-919	11,411	-11,328	6,499	-6,416	-826	910
DAE	33	-	88	-55	116	-83	30	3	2,845	-2,813	-2	35	1,177	-1,145	1,150	-1,117
Brazil	103	-	27	76	45	58	691	-588	12,141	-12,038	921	-817	6,283	-6,180	5,327	-5,223
ROW	265	-	397	-133	375	-110	1,542	-1,278	637	-372	1,044	-780	2,082	-1,818	-149	414
Total	4,071	-	4,071	2,168	4,071	2,058	4,071	13,319	4,071	19,219	4,071	15,393	4,071	17,330	4,071	16,546
Standard deviation	651	-	442	-	399	-	2491	-	4,450	-	3,886	-	3,446	-	3,787	-

Note: All figures are expressed in billion US$.

For the base case, it is not surprising that individual rationality is violated for EE and China because their marginal benefits and abatement costs are far below average levels. Hence, these regions contribute above average to global pollution control but benefit only below average. Obviously, none of the permit schemes simultaneously repairs this deficiency for these two regions, letting alone the violation of individual rationality of other regions.

Fourth, even though we can immediately conclude that the grand coalition is not a stable coalition structure because individual rationality is violated under all schemes, it may nevertheless be possible to form smaller coalitions that are individually rational. Nevertheless, also for smaller coalitions stability may be a problem as will be apparent from the next section.

IV. Stability analysis

In this section, we present results of our stability analysis. We start with the "standard case" in section IV.A, reflecting the parameter values as reported and discussed in section III. In section IV.B, we report on the results of our sensitivity analysis.

A. Standard case

For each scenario, we test all 4084 coalition structures for stability with an algorithm programmed in Matlab. In the base case without permit trading, it turns out that more than 1000 coalition structures are externally stable but only 14 coalition structures are internally stable. None of the 13 non-trivial coalition structures (i.e., including a coalition of at least two members) that are internally stable are also externally stable and hence no non-trivial coalition structure is stable. On the one hand, this stresses that internal stability is the main problem of stability and therefore we focus in particular on this part of stability in the following discussion. On the other hand, this stresses the strong free-rider incentives in general, but, in particular, in the context of heterogeneous regions.

Under the scenario "Quota-BAU", this changes somehow. Now 28 coalition structures are internally stable of which two are also externally stable. The first coalition structure includes a coalition between the European Union (EU-15) and China and the second a coalition between India and the "Rest of the World" (ROW). In order to explain the driving forces of permit trading, we exemplarily have a closer look at the coalition between EU-15 and China in Table 3, though similar relations are also true for other stable coalitions.

Table 3. Coalition between the European Union and China: No permit trading and permit trading under the Quota BAU scenario

Regions	Total emission reduction		Marginal abatement costs	Payoffs (without permit trading)	Payoffs (with permit trading)	Transfers	ICM (without permit trading)	ICM (with permit trading)
	gton (over 100 years)		US$/ton	bln US$ over 100 years	bln US$ over 100 years	bln US$ over 100 years	bln US$ over 100 years	bln US$ over 100 years
	q_i^*	$\bar{q}_i$		π_i	$\tilde{\pi}_i$			
USA	16	-	8.5	683	683	-	137.8	-132.6
Japan	1	-	6.5	559	559	-	107.9	-25.0
EU-15	8	20	11.1	733	595	137	-268.6	-131.3
O-OECD	2	-	1.3	111	111	-	-13.5	-52.3
EE	1	-	0.5	42	42	-	-19.4	-40.8
FSU	5	-	2.5	215	215	-	-13.7	-64.2
EEX	1	-	1.1	97	97	-	-21.3	-139.2
China	46	34	11.1	-6	131	-137	118.0	-19.3
India	3	-	1.9	160	160	-	-30.2	-11.2
DAE	1	-	0.9	81	81	-	-18.1	-33.5
Brazil	0	-	0.6	50	50	-	-0.4	-18.7
ROW	4	-	2.5	217	217	-	-14.3	-24.1
World	87	-	-	2,942	2,942	-	-	-

Note: ICM means incentive to change membership measured as $\pi_i(\sigma_i', \sigma_{-i}^*) - \pi_i(\sigma_i^*, \sigma_{-i}^*)$. See section II.A.

From Table 3, it is evident that without permit trading the coalition between the EU-15 and China (indicated in italics in the first column) is not internally stable because China would gain by leaving this coalition (indicated in the second last column). Clearly, without transfers, EU-15 is the main beneficiary in this coalition at the expenses of China. Because China is a cheap provider of abatement, also USA and Japan have an incentive to join this coalition (indicated in the second last column) and therefore this coalition would also not be externally stable.

With permit trading, the situation changes. Under the "Quota BAU" scenario, China receives a sufficient amount of emission permits ($\bar{q}_i$ is low; see equation 7) that can be sold to EU-15. Thus, China receives a large transfer of 137 billion US$ as indicated in the column "Transfers". Thus, whereas before there was a slack of enforcement power on the side of EU-15 and lack on the side of China without permit trading, this asymmetry is now somehow mitigated with permit trading, as this is evident from the last column. Now China would loose from leaving the coalition. Also no outsider has an incentive to join the coalition. In particular, USA and Japan have no interest anymore in joining this coalition because transfers to China would exceed their gains from cooperation.

For the other coalitions and permit trading schemes, results are summarized in Table 4.

In Table 4, the singleton coalition structure, which is stable by definition, and the grand coalition structure, which is not stable under any scenario, are listed as benchmarks to measure the success of stable coalition structures. Also the reference case without permit trading is listed. It is evident that under the pragmatic schemes the number of internally stable coalition structures is higher than in the base case without permit trading but under the equity schemes this is substantially lower. This confirms the conjecture from the grand coalition in section III.B that equity schemes may remove an asymmetry but replace it by a different and even stronger asymmetry. Different degrees of asymmetry also show up in terms of stable coalition structures (internally and externally stable coalition structures). Only under the pragmatic schemes, we find stable coalition structures. Those stable coalition structures improve upon the non-cooperative situation in environmental and welfare terms, though they close the gap between no and full cooperation only to a small extent. The results also confirm that membership matters and that from the number of participants success cannot be inferred. For example, the coalition between EU-15 and China is more successful than any other stable coalition, though the coalition between EU-15, Eastern European countries (EE) and India counts one more member.

B. Sensitivity analysis

A typical feature of empirical work is that results depend on assumptions about policy scenarios and on parameter values, which are subject to some uncertainty. In terms of policy scenarios, we considered above two pragmatic and five equity allocation schemes of permits. It is evident that a much longer list of schemes could be generated and checked for stability. We refrain from this exercise. However, given that the two pragmatic schemes perform rather well whereas all

Table 4. Stable coalition structures

Scenario	Number of internally stable coalitions	Stable coalitions	Global emission reduction	Global payoff
(i) singleton coalition	-	stable	55	1,960
(ii) no permit trading	14	no stable coalitions	-	-
(iii) (1) quota BAU	28	{EU-15, China}	87	2,942
		{India, ROW}	60	2,107
(2) quota Nash	53	{EU-15, EE, India}	68	2,372
		{Japan, India}	61	2,151
(iv) (3) egalitarian	3	no stable coalitions	-	-
(4) historical responsibility	1	no stable coalitions	-	-
(5) ability to pay	0	no stable coalitions	-	-
(6) ability to pollute	1	no stable coalitions	-	-
(7) energy efficiency	1	no stable coalitions	-	-
(v) grand coalition	-	not stable	256	6,031

Notes: Global emission reduction = giga tons over 100 years. Global payoff = billion US dollar over 100 years. Stable coalitions means internally and externally stable. Scenarios 1 and 2 correspond to the" pragmatic schemes" and scenarios 3 to 7 to the "equitable schemes".

five equity schemes perform badly for our model, one may wonder whether a combination of a pragmatic and an equity rule would perform better. Thus, we tested a combination of every of the two pragmatic schemes with every of the five equity schemes. We consider apart from a 50%/50% allocation rule of permits, also a 25%/75% and 75%/25% rule.[6] Surprisingly, we find no non-trivial coalition structure that is stable. Apparently, the equity rules introduce too much asymmetry, or, put differently, the asymmetry of the equity schemes cannot be sufficiently balanced by the pragmatic schemes. Thus, the superiority of the pragmatic schemes over the equity schemes in our model is confirmed by our sensitivity analysis.

In terms of parameters and given the large number of parameters that enter our model, some selection is necessary for a sensitivity analysis. We believe that the highest uncertainty concerns benefits from global abatement and discounting. Hence, in terms of benefits, we conduct a sensitivity analysis where we uniformly

[6] This means that we tested 30 additional scenarios.

raise the level of benefits from global abatement. That is, we raise the base value of the global benefit parameter μ_B from 100 to 200 and 300 percent.[7] In terms of the discount factor, we recall that our "standard case" assumed a discount rate of 2 percent. This is roughly in line with Weitzman (2001) who suggests that if a constant discount rate has to be chosen, in the context of global warming, then a discount rate of 2 percent or less is appropriate to capture long-term effects. This means that we are at the upper bound. Hence, we test also for a discount factor of 1 percent and - in order to get a more complete picture of the driving forces - consider additionally also a discount rate of 3 percent. It is evident that discounting affects not only benefits but also abatement costs. In line with more sophisticated models, a lower (higher) discount rate means in our model STACO to put a higher (lower) weight on benefits compared to abatement costs because of the long terms effects of climate change. More specifically, a change in the discount rate affects the benefit parameter δ_B and the cost parameter δ_c in STACO. Since both parameters are level parameters (see equation (6); as this is also true for μ_B), only the change of the relation δ_B / δ_c is important. Hence, a discount rate of 1 percent has the same effect as raising the global benefit parameter μ_B from 100 to 120 percent and a discount rate of 3 percent has the same effect as lowering the global benefit parameter μ_B from 100 percent to 85 percent.

Hence, taken together, our sensitivity analysis compares our standard scenario, which is the 100 percent scenario, with a 85, 120, 200 and 300 percent scenario. Table 5 summarizes the results that confirm our qualitative results from above.

First, the grand coalition, though it would raise global welfare substantially compared to no cooperation, is not stable under all scenarios.

Second, without permit trading, there is now one stable coalition structure in the 120, 200 and 300 percent scenarios that involves a coalition between Japan and EU-15.[8] This suggests that a sufficient high recognition of the benefits from controlling global warming may improve upon the prospects of cooperation – a conjecture confirmed for the pragmatic permit trading schemes. However, this coalition only slightly improves upon the non-cooperative outcome: both regions have steep marginal abatement costs and therefore only marginally increase abatement efforts above non-cooperative levels.

Third, pragmatic permit trading schemes are superior to equitable schemes for

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[7] Recall, μ_B = 0.027 in the base case and hence 200 (300) percent implies μ_B = 0.054 (μ_B = 0.081) which means a substantial increase in the valuation of the benefits from a reduction of greenhouse gases. This is certainly a optimistic view with respect to the recognition of environmental benefits by governments.

[8] It turns out that 120 percent is the lower benchmark for which this change occurs.

Table 5. Sensitivity analysis

Percentage parameter μ_B	Coalitions	Scenarios				Total emission reduction	Global payoff
		No permit trading	(1)	(2)	(3) to (7)	gton (over 100 years)	bln US$ (over 100 years)
	Singleton coalition structure	x	x	x	x	50	1,493
	Coalition Japan, EU-15	-	-	-	-	53	1,567
	Coalition India, ROW	-	x	-	-	54	1,607
85 %	Coalition Japan, India	-	-	x	-	55	1,641
	Coalition EU-15, EE, India	-	-	x	-	62	1,814
	Coalition EU-15, China	-	x	-	-	78	2,253
	Grand coalition	-	-	-	-	234	4,656
	Singleton coalition structure	x	x	x	x	55	1,960
	Coalition Japan, EU-15	-	-	-	-	59	2,056
100 %	Coalition India, ROW	-	x	-	-	60	2,107
Base	Coalition Japan, India	-	-	x	-	61	2,151
Case	Coalition EU-15, EE, India	-	-	x	-	68	2,372
	Coalition EU-15, China	-	x	-	-	87	2,942
	Grand coalition	-	-	-	-	256	6,031
	Singleton coalition structure	x	x	x	x	62	2,655
	Coalition Japan, EU-15	x	-	-	-	67	2,784
	Coalition India, ROW	-	x	-	-	67	2,850
120 %	Coalition Japan, India	-	x	x	-	69	2,909
	Coalition EU-15, EE, India	-	-	-	-	77	3,199
	Coalition EU-15, China	-	x	-	-	98	3,962
	Grand coalition	-	-	-	-	284	8,053
	Singleton coalition structure	x	x	x	x	87	6,161
	Coalition Japan, EU-15	x	-	-	-	92	6,453
	Coalition India, ROW	-	x	-	-	93	6,588
200 %	Coalition Japan, India	-	x	x	-	95	6,720
	Coalition EU-15, EE, India	-	-	-	-	105	7,343
	Coalition EU-15, China	-	x	x	-	133	9,045
	Grand coalition	-	-	-	-	377	18,000

Table 5. (Continued) Sensitivity analysis

Percentage parameter μ_B	Coalitions	Scenarios				Total emission reduction	Global payoff
		No permit trading	(1)	(2)	(3) to (7)	gton (over 100 years)	bln US$ (over 100 years)
	Singleton coalition structure	x	x	x	x	112	11,910
	Coalition Japan, EU-15	x	-	-	-	119	12.466
	Coalition India, ROW	-	x	-	-	119	12,704
300 %	Coalition Japan, India	-	x	x	-	122	12,950
	Coalition EU-15, EE, India	-	-	-	-	135	14,094
	Coalition EU-15, China	-	x	x	-	169	17,280
	Grand coalition	-	-	-	-	470	33,903

Note: "x" means stable and "–" means not stable. First column refers to "percentages of the benefit parameter" μ_B. The 85 and 120 percent scenario correspond to a discount rate of 3 and 1 percent, respectively, as explained in the text. Scenarios 1 and 2 correspond to the "pragmatic schemes" and scenarios 3 to 7 to the "equitable schemes".

all scenarios. Apart from the singleton coalition structure, there is no stable coalition structure under any equitable scheme but two or three under the pragmatic schemes. Thus, our conclusion from above is confirmed that moral motivations (i.e., equity concerns) may not always be a good guide for successful treaty-making.

Fourth, in case there are stable coalition structures, they involve only small coalitions and only marginally improve upon the non-cooperative outcome in terms of global welfare and global emission reduction. Thus, even though a cleverly designed permit trading scheme may balance some asymmetries between coalition members, it cannot totally overcome strong free-rider incentives.

V. Summary and conclusions

We studied the effect of permit trading on the stability of global climate agreements with a model that combines a game theoretical with an empirical module.

The game theoretical module models coalition formation as a two-stage game in which regions choose their participation in an agreement in the first stage and their abatement strategies in the second stage. Apart from membership, payoffs depend on the permit trading scheme, implying different initial allocations of emission allowances. The empirical module provided benefit and costs estimates for twelve world regions. Though it captures long-run effects of greenhouse gas accumulation over 100 years, it assumes stationary abatement strategies for game theoretical tractability.

We considered seven different permit trading schemes that were divided into two categories: "pragmatic" and "equitable" schemes. Pragmatic schemes are closely related to the current status quo and allocate permits according to uniform emission reductions from some base emission level. We considered emissions in the business-as-usual scenario without abatement and those in the Nash equilibrium as base lines. Equitable schemes could be motivated by different notions of fairness that have been proposed in the literature as for instance "historical responsibility" or "ability to pay". From the many results we would like to mention three key results.

First, the gains from partial and full cooperation would be very large in terms of global welfare but also measured in environmental variables like global emission reduction. However, the gains are quite unevenly distributed because of the large heterogeneity between regions. Depending on the permit scheme, this inequality can be mitigated, as for instance the pragmatic schemes do. However, the equitable schemes frequently replace one type of asymmetry by introducing another asymmetry, implying large transfers from one group of countries to another group. For instance, a scheme that allocates permits on a per capita basis implies large transfers from industrialized to developing countries.

Second, the large asymmetries under the equitable rules found for full cooperation also showed up for partial cooperation, implying that there was no stable coalition under equitable schemes. In contrast, some coalitions are stable under the pragmatic schemes. Thus, our findings do not support the conjecture that equity can enhance the success of agreements. Of course, this finding cannot claim generality. Nevertheless, it provides an indication that equity principles alone might not be able to offset strong-free-rider incentives. In fact, designing permit trading schemes based on pragmatic principles may appear to be less fair but more successful in mitigating the climate problem.

Third, even cleverly designed permit trading schemes that reduces the disparity of the allocation of the gains from cooperation cannot overcome strong free-rider incentives. In our model, only small coalitions turned out to be stable that improve upon the status quo, though not much. Nevertheless, it became evident that the number of participants is not a good indicator for the success of treaties, membership may be even more important. This suggests that when designing a permit scheme for future agreements, identifying key players and inducing the participation of those players should receive a high priority.

For future research, we would like to mention four items among many other possibilities. First, we could drop the assumption of joint welfare maximization within a coalition. The assumption implies that ambitious abatement targets are implemented. This translates into instability of large coalitions because of high free-rider incentives. Overall, it is likely that better results may be achieved if members settle for less ambitious abatement targets. If the effect on participation is strong enough, this may well compensate for modest abatement targets (Finus and Rundshagen 1998). Second, we could drop the assumption that permits are only traded among coalition members. This would closely resemble the clean development mechanism under the Kyoto Protocol where signatories can also buy certified emission reductions from non-signatories. Obviously, this option could reduce abatement costs of signatories and thus increase their welfare. However, this option also increases welfare of non-signatories through transfers. Thus, it is not evident whether such an option will raise self-enforcing participation and the success of treaties. However, there is no doubt that a consistent treatment of this issue will complicate the analysis substantially because the determination of optimal abatement levels will have to consider all strategic aspects associated with world wide trade. Third, though we already considered a substantially larger number of actors than most climate models, twelve regions is nevertheless a small number compared to the total number of countries world wide. From the theory of public goods, we expect that a larger number of actors would enhace free-riding problems. That is, our aggregation into 12 world regions means an optimistic view to the possibilities of self-enforcing cooperation. However, currently, the problem of such an extension is the lack of less aggregated empirical data. Fourth, we limited the decision about participation to a one-shot decision for simplicity. A more realistic and interesting assumption would allow for the possibility that decisions can be revised at various points in time. It is evident that this would also require giving up the assumption of stationary abatement strategies in order to render the analysis relevant. On the one hand, this would allow accounting for a change of benefit and abatement parameters over time which seems important in the context of a long time horizon. On the other hand, we expect that already for a setting with “only” twelve heterogeneous players, this would constitute a great computational challenge as results for symmetric players and simple payoff functions in Rubio and Ulph (2003) indicate.

Appendix

Table A1. Emissions, benefit and abatement cost parameters

Regions	Emissions in 2010 (Gton)	Share of global benefits γ_i	Abatement cost parameter α_i	Abatement cost parameter β_i
1 USA	2.42	0.226	0.0005	0.00398
2 Japan	0.56	0.173	0.0155	0.18160
3 European Union (EU-15)	1.4	0.236	0.0024	0.01503
4 Other OECD Countries (O-OECD)	0.62	0.035	0.0083	0
5 Eastern European Countries (EE)	0.51	0.013	0.0079	0.00486
6 Former Soviet Union (FSU)	1	0.068	0.0023	0.00042
7 Energy Exporting Countries (EEX)	1.22	0.030	0.0032	0.03029
8 China	2.36	0.062	0.00007	0.00239
9 India	0.63	0.050	0.0015	0.00787
10 Dynamic Asian Economies (DAE)	0.41	0.025	0.0047	0.03774
11 Brazil	0.13	0.015	0.5612	0.84974
12 Rest of the World (ROW)	0.7	0.068	0.0021	0.00805
World	11.96	1	-	-

Note: Input data in STACO-model as described in Finus, Altamirano, Cabrera, van Ierland (2004).

Table A2. Base data for allocation of permits

Regions	Emissions in BAU scenario (1)	Emissions in Nash scenario (1)	Population (2)(4)	GDP (3)(4)	GDP per capita (5)	Emissions per capita (BAU-scenario) (6)	Emissions per unit of GDP (BAU-scenario) (7)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	(gton)	(gton)	(million of habitants)	(billion 1985 US$)	(thousand 1985 US$)	(tons per habitant)	(tons per 1985 US$)
USA	2.4	226	305	8,845	29.0	79	0.03
Japan	0.5	55	124	5,584	44.9	45	0.01
EU-15	1.4	133	375	9,579	25.5	37	0.01
O-OOE	0.6	60	142	1,902	13.4	44	0.03
EE	0.5	51	120	405	3.4	43	0.13
FSU	1	95	287	501	1.8	35	0.20
EEX	1.2	121	1,602	1,650	1.0	8	0.07
China	2.4	221	1,340	1,021	0.8	18	0.23
India	0.6	61	1,145	458	0.4	6	0.14
DAE	0.4	40	207	972	4.7	20	0.04
Brazil	0.1	13	190	774	4.1	7	0.02
ROW	0.7	66	584	1,119	1.9	12	0.06
WORLD	11.9	1,140	6,421	32,810	-	-	-

Notes: (1) STACO calculations (Finus/Altamirano-Cabrera/van Ierland 2004). (2) population in 2010 calculated from table 2.1 of World Bank (2002). (3) GDP in 2010 calculated from DICE model and table 1.1 of World Bank (2002). (4) Data aggregated into STACO's 12 regions following Babiker et al. (2001). (5) Computed from column 3 and 4. (6) Computed from column 1 and 3. (7) Computed from columns 1 and 4.

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