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# Participation in International Environmental Agreements: The Role of Timing and Regulation

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# Participation in International Environmental Agreements: The Role of Timing and Regulation

## Summary

We analyze the formation of self-enforcing international environmental agreements under the assumption that countries announce their participation either simultaneously or sequentially. It is shown that a sequential formation process opens up possibilities for strategic behavior of countries that may lead to inferior outcomes in terms of global abatement and welfare. We then analyze whether and under which conditions a regulator like an international organization, even without enforcement power, can improve upon globally suboptimal outcomes through coordination and moderation, given that recommendations must be Pareto-improving to all parties.

**Keywords:** International environmental agreements, Timing of participation decision, Coalition theory, Role of international regulator

**JEL Classification:** C72, D70, H41, Q50

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# 1. Introduction

A major assumption in the game theoretical oriented literature analyzing international environmental agreements (IEAs) is the absence of a supranational body with enforcement power. That is, IEAs must be *self-enforcing*. This has been tested with the stability concept of internal and external stability (e.g., Barrett 1994, Buchholz and Peters 2003, Carraro and Siniscalco 1993 and Hoel 1992) and the concept of the core (e.g., Chander and Tulkens 1997 and Germain, Tulkens, Toint and de Zeeuw 2003).[1] Both concepts are quite different and therefore lead to very different predictions about stable coalitions.[2] For instance, the concept of internal and external stability predicts only small stable coalitions, defines stability only in terms of single deviations (i.e., only single countries can join or leave a coalition), restricts coalition formation to only one non-trivial coalition (i.e., a coalition of at least two countries) and implies open membership (i.e., any country can join the coalition) and therefore no consensus about participation. In contrast, the concept of the core predicts only the grand coalition as a stable outcome, defines stability in terms of multiple deviations, allows for the coexistence of several (multiple) coalitions (though in equilibrium only the grand coalition forms) and implies de facto exclusive membership as well as unanimity of all members about participation. However, both concepts share the implicit assumption that coalition formation takes place simultaneously. That is, all countries simultaneously announce their participation decision and in equilibrium no single country (internal and external stability) or no group of countries (core) has an incentive to change announcements, given the announcements of other countries. Moreover, regardless of the applied concept, all models have ignored the role of international organizations like UNEP (United Nations Environmental Program) or working groups like COP or MOP (Conferences/Meetings of the Parties) in preparing and shaping IEAs.

On the one hand, it is evident that a simultaneous decision about participation is certainly a valid but not the only possible assumption. In fact, casual empirical evidence on international environmental negotiations suggests that longlasting and sequential decision processes are not unlikely. That is, an initiator kicks off the negotiation process with a proposal. Other countries accept or make a new proposal. This process continues until some or no agreement is reached. Therefore, the first item of this paper is the role of timing in negotiations. That is, we compare the outcome of a simultaneous with a sequential coalition formation process where we follow

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[1] For an overview of the game theoretical literature on international environmental agreements, see for instance Finus (2001), Folmer and de Zeeuw (1999) and Xepapadeas (1997).

[2] For a systematic comparison of both concepts, see for instance Finus (2003) and Tulkens (1998).

the mainstream of the literature and model coalition formation as two stage-game. In the first stage, countries choose their participation and in the second stage, they choose their abatement strategies and possible compensation payments. For analytical reasons, we stick to the widely made assumption of symmetric players (i.e., all countries have the same payoff function). This has also the advantage that the bargaining over abatement strategies and compensation payments within coalitions has an obvious solution (see section 2 for details). However, we neither want to rule out a priori the possibility of multiple coalitions nor do we want to define stability only in terms of single deviations. Moreover, for a consistent comparison, we have to choose two membership games that share all features except the timing of the decision about participation. Therefore, we select from the recent literature on coalition theory (see, e.g., Bloch 2003 and Yi 1997) the Γ–game of Hart and Kurz (1983) that we call simultaneous move unanimity game and the sequential move unanimity game of Bloch (1995). In the first game, we define equilibrium coalition structures using the concept of strong Nash equilibrium and in the second game we apply the concept of subgame-perfect equilibrium.

On the other hand, it seems premature to ignore the role of international institutions in the analysis of IEAs (as the bulk of the literature has done) because they have no enforcement power. From a positive point of view, this means that we cannot explain the frequent involvement of these institutions in the preparation of almost every past IEA. From a normative point of view, we possibly ignore an important factor that may help to mitigate free-riding. After all, even without enforcement power, these institutions, which we summarize under the term “regulator” henceforth, may play an important role as a coordinator or moderator during negotiations leading to an IEA. Therefore, the second item of this paper is the role of regulation. That is, we analyze whether and under which conditions a regulator can improve upon the outcome in the simultaneous and sequential move unanimity game without regulation.

In the following, we present our model of coalition formation in section 2. In section 3 and 4, we characterize and compare equilibrium coalition structures in the two membership games with and without regulator, respectively. Section 3 and 4 consider an analytically simple case and section 5 discusses extensions. Section 6 raps up the discussion and points to some possible issues of future research.

# 2. Model of Coalition Formation

## 2.1 Introduction

Coalition formation is modeled as a two-stage game. In the first stage, countries which may be indexed by $i \in I=\{1, \ldots, N\}$ choose their membership strategy; in the second stage, they choose their abatement strategy. In the first stage, we consider two membership games. The first game assumes that countries decide upon their membership simultaneously, the second game assumes that they do this sequentially. Both membership games allow for the co-existence of multiple coalitions. Hence, the choice in the first stage leads to some coalition structure $c=\{c_1, \ldots, c_M\}$ where $c \in C$ is a partition of countries in disjoint non-empty sets, $c_\ell \cap c_m = \emptyset \ \forall \ \ell \neq m$ and $\bigcup_\ell c_\ell = I$.[3] In the second stage, we follow the standard assumption in the literature (see, e.g., Bloch 2003) and assume that members of coalition $c_\ell$ in coalition structure c choose their abatement strategies such as to jointly maximize the aggregate payoff to their coalition. The simultaneous solution of this maximization problem for all coalitions $c_i \in c$ leads to an equilibrium abatement vector which is associated with payoff vector $\pi(c) = (\pi_1(c_\ell, c), \ldots, \pi_N(c_n, c))$. That is, a coalition structure $c \in C$ is mapped into a vector of individual payoffs $\pi(c) \in \Pi(C)$ called valuation where the first argument in $\pi_i(c_\ell, c)$ refers to the coalition to which country i belongs and the second to the coalition structure. In our model there is a unique equilibrium abatement vector for every coalition structure $c \in C$ and hence valuations are unique. The two-stage game is solved by backwards induction. Accordingly, in the following, we discuss first the second stage and then move on to the first stage of coalition formation.

## 2.2 Second Stage of Coalition Formation

Since multiple coalitions and a sequential coalition formation process introduce some complexity compared to standard coalition models, we assume symmetric countries with the following payoff function:[4]

$$[1] \qquad \pi_i = \beta\left(\sum_{j=1}^{N} q_j\right) - \chi(q_i)$$

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[3] For instance, in the case of N=3, C comprises 5 different coalition structures: {{1},{2},{3}}; {{1,2},{3}}; {{1,3},{2}}; {{1},{2,3}} and {{1,2,3}}.

[4] The assumption of symmetric players is very common. For a similar assumption in the context of IEAs, see for instance Barrett (1994), Carraro and Marchiori (2003), Carraro and Siniscalco (1993) and Rubio and Ulph (2003); in the context of other economic problems, see the literature cited in Bloch (2003) and Yi (1997).

and with the following properties:

$\beta^{'} > 0$, $\beta^{''} \leq 0$ , $\chi^{'}(0) = 0$ , $\chi^{'}(q_i) > 0$ for $q_i \in (0, q^{max}]$, $\lim_{q_i \to q^{max}} \chi'(q_i) = \infty$, $\chi^{''} > 0$ .

That is, we assume that abatement costs $\chi$ increase in individual abatement $q_i$ at an increasing rate and benefits $\beta$ from global abatement $\sum_{j=1}^{N} q_j$ increase at constant or decreasing rate. Hence, we assume an environmental problem where emissions uniformly mix in the atmosphere like CFCs and greenhouse gases and hence global abatement is the sum of individual abatement. The other properties listed above ensure an interior solution for the assumption that all coalition members choose their optimal abatement level by maximizing the aggregate welfare to their coalition, taking the abatement level of all other countries as given:[5]

$$[2] \qquad \max_{(q_i)_{i \in c_\ell}} \sum_{k \in c_\ell} \pi_k$$

which gives rise to the following first order conditions:

$$[3] \qquad |c_\ell| \beta^{'}(\sum_{j=1}^{N} q_j) = \chi^{'}(q_i) \,,\ \forall\, i \in c_\ell \,,\ \forall\, c_\ell \in c$$

where $|c_\ell|$ denotes the size of coalition $c_\ell$. The simultaneous solution of the N first order conditions delivers an abatement vector $q^*(c) = (q_1^*(c_\ell, c), ..., q_N^*(c_n, c))$ associated with coalition structure c. This abatement vector constitutes de facto a Nash equilibrium between coalitions. As shown in Finus, van Mouche and Rundshagen (2004), this equilibrium is unique for each coalition structure $c \in C$. Hence, substitution of equilibrium abatement levels into [1] gives unique valuations $\pi(c) \in \Pi(C)$. Moreover, it is evident that if all countries form only a singleton coalition ($|c_\ell| = 1 \ \forall\, c_\ell \in c$), the equilibrium abatement vector corresponds to the "classical" Nash equilibrium and if all countries are in one coalition (grand coalition; $|c_\ell| = N$), this is the "classical" global or social optimum.

The first order conditions in [3] can be interpreted as implicit best reply or reaction functions and hence it is evident that countries have a dominant strategy if $\beta^{''} = 0$ (because then $\beta^{'}$ is a

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[5] This frequent assumption seems not controversial in our context, though it may be questioned in general. First, coalitional and individual rationality within a coalition coincide for all members if players are symmetric. That is, maximizing joint welfare means maximizing individual welfare of every coalition member. Second, this assumption means symmetric payoffs for all members of the same coalition and hence compensation payments can be ignored. Clearly, heterogeneous players would suggest to model the choice of abatement strategies and compensation payments as a bargaining process. See Maskin (2003) and Ray/Vohra (1999) for a first attempt in this direction.

constant). This is the case if the benefit function is linear (Folmer and van Mouche 2002). In contrast, if $\beta'' < 0$, countries have no dominant strategy which is the case for non-linear or strictly concave benefit functions.[6]

It will turn out that payoff functions implying dominant strategies are analytically easier to handle than their counter-parts. Therefore, in a first step, we restrict the analysis of equilibrium coalition structures without (section 3) and with (section 4) regulator to the simpler case. Subsequently, we extend the analysis to non-dominant strategies in section 5. In the remainder of this subsection, we derive four properties that will prove helpful for the subsequent analysis.

From the first order conditions in [3], it is evident that all members of coalition $c_\ell$ will choose the same abatement level. Moreover, in any coalition structure c and for any aggregate abatement level $\sum_{j=1}^{N} q_j$, differences in individual abatement levels between coalitions are only related to the size of coalitions. Hence, all members of coalition $c_\ell$ receive the same payoff which only depends on the size of coalition $c_\ell$. Since $\chi' > 0$ and $\chi'' > 0$, $q_i^*(c_\ell, c) < q_j^*(c_m, c)$ will hold in equilibrium if $|c_\ell| < |c_m|$. Consequently, abatement costs of coalition members in $c_\ell$ will be lower than of coalition members in $c_m$. Since all countries receive the same benefits from global abatement, payoffs to coalition members in $c_\ell$ will be higher than payoffs to coalition members in $c_m$.

These relations suggest that we can simplify notation in the following. A coalition structure $c = \{c_1, ..., c_M\}$ may be identified by the vector of coalition sizes where we follow the convention and list coalitions according to decreasing size, i.e., $|c_1| \geq |c_2| \geq ... \geq |c_M|$, and write only $c_\ell$ instead of $|c_\ell|$. Hence, in a context where only the coalition sizes are important, we write $c = (c_1, ..., c_M)$. Accordingly, we write valuations $\pi(c) = (\pi_{c_1}, ..., \pi_{c_M})$ in ascending order of payoffs with the understanding that all countries belonging to coalition $c_\ell$ receive payoff $\pi_{c_\ell}$. We summarize our observation from above in the following property.

### Property 1: Individual Abatement, Individual Payoff and the Size of Coalitions

*a) Members of smaller coalitions choose a lower abatement level in any given coalition structure* $c \in C$. *That is,* $q_i^*(c_\ell, c) < q_j^*(c_m, c)$ *for all* $i \in c_l, j \in c_m$ *iff* $c_\ell < c_m$.

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[6] For payoff functions that imply dominant strategies, see for instance Botteon and Carraro (1997), Hoel (1992), Hoel and Schneider (1997), Petrakis and Xepapadeas (1996) as well as Stähler (1996) and for those that imply non-dominant strategies, see for example Barrett (1994), Diamantoudi and Sartzetakis (2001) and Finus and Rundshagen (1998).

*b) Members of smaller coalitions enjoy a higher payoff than members of larger coalitions in any given coalition structure c∈C. That is,* $\pi_i(c_\ell, c) > \pi_j(c_m, c)$ *for all* $i \in c_l$, $j \in c_m$ *iff* $c_\ell < c_m$.

Note that Property 1a means for payoff functions implying dominant strategies that abatement levels of smaller coalitions will be lower than those of larger coalitions in *every* coalition structure and not only in a given coalition structure.

Also from the first order conditions in [3], though less evident, a second property about the relation between different coalition structures and global abatement follows. This property uses the terms *coarsening* and *concentration* (Yi 1997 and Bloch 2003). A coalition structure $c = (c_1, ..., c_M)$ is said to be coarser than coalition structure $\hat{c} = (\hat{c}_1, ..., \hat{c}_{\hat{M}})$, $M < \hat{M}$, if and only if c can be derived by a merger or sequence of mergers of coalitions in $\hat{c}$. For example, coalition structure c=(6,5) is coarser than coalition structure $\hat{c} = (5,5,1)$. In case coalition structures cannot be compared under the criterion of coarsening, as this is for instance the case for $\tilde{c} = (5,5)$ and $\overset{\frown}{c} = (6,4)$, the criterion of concentration may be helpful. A coalition structure $c = (c_1, ..., c_M)$ is said to be more concentrated than $\hat{c} = (\hat{c}_1, ..., \hat{c}_{\hat{M}})$, $M \leq \hat{M}$, if and only if c can be derived from $\hat{c}$ by a single move or a sequence of moves where one member at a time from a coalition $\hat{c}_m$ in coalition structure $\hat{c}$ is moved to another coalition $\hat{c}_\ell$ of equal or larger size. Through this process, coalitions in $\hat{c}$ *may* be sequentially dissolved. For instance, c=(6,4) is a concentration of $\hat{c} = (5,5)$ or $\hat{\hat{c}} = (6,3,1)$. It is evident that every coalition c which is coarser than coalition $\hat{c}$ implies that c is more concentrated than $\hat{c}$, though the opposite is not true (see Yi 1997).[7]

**Property 2: Global Abatement, Coarsening and Concentration**

*a) Let coalition structure c be coarser than coalition structure* $\hat{c}$*, then global abatement in c is higher than in* $\hat{c}$*. That is,* $\sum_{j=1}^{N} q_j(c) > \sum_{j=1}^{N} q_j(\hat{c})$.

*b) Let coalition structure c be more concentrated than coalition structure* $\hat{c}$*, then global abatement in c is higher than in* $\hat{c}$ *if* $2\chi''^2 > \chi'\chi'''$*. That is,* $\sum_{j=1}^{N} q_j(c) > \sum_{j=1}^{N} q_j(\hat{c})$.

From Property 2, it is evident why we distinguish between coarsening and concentration, though the latter criterion is finer: Property 2a can be established at a general level whereas Property 2b requires a slightly more specific assumption (Yi 1997). However, note that most

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[7] Note that also concentration may not allow for a complete ordering of coalition structures. For instance, c=(4,3) and $\hat{c} = (5,1,1)$ cannot be ranked under concentration, though for our purposes this problem will prove to be irrelevant.

cost functions assumed in the literature on international environmental agreements satisfy the (sufficient) condition $2\chi''^2 > \chi'\chi'''$ as for instance power functions $\chi = \gamma q_i^{\omega}$, $\gamma > 0$, $\omega > 1$, or exponential functions $\chi = \alpha e^{\beta q_i}$, $\alpha > 0$, $\beta > 0$.

Property 2 allows for two more conclusions. The first conclusion is that the highest global payoff will be obtained in the coalition structure with the grand coalition. In this case, the assumption of joint welfare maximization implies to maximize the aggregate payoff of all countries. Hence, the global payoff must be at least as high as in any other coalition structure. Thus, it remains to stress why the global payoff is *strictly* higher than in any other coalition structure: 1) The grand coalition is coarser than any other coalition structure. 2) Hence, global abatement is strictly higher than in any other coalition structure according to Property 2a. 3) Consequently, the (unique) abatement vector in the grand coalition will differ from any other coalition structure.

**Property 3: Global Payoff**

*The global payoff in the coalition structure that comprises only the grand coalition is strictly higher than in any other coalition structure. That is,* $\sum_{j=1}^{N} \pi_j(c) > \sum_{j=1}^{N} \pi_j(\hat{c})$ *where* $c = (N)$, $c \neq \hat{c}$ *and* $c, \hat{c} \in C$.

The second conclusion from Property 2 is that countries not involved in a coarsening or a concentration (outsiders) will be better off through such a change in the coalition structure. Because global abatement increases (see Property 2), marginal benefits of “outsiders” decrease ($\beta'' < 0$) or remain constant ($\beta'' = 0$). For countries not involved in a coarsening or concentration the size of their coalition $c_n$ remains constant. Hence, the left hand sight of the first order conditions in [3] remains constant or decreases and hence because of $\chi' > 0$ and $\chi'' > 0$, outsiders will either not change or decrease their abatement level. Consequently, outsiders′ benefits will be higher and their abatement costs will be the same or smaller after a merger or concentration.

**Property 4: Positive Externality**

*a) Members of coalitions that are not involved in a merger of coalitions are better off after the merger. That is,*

$\pi_i(c_n, c) > \pi_i(c_n, \hat{c})$ *for all* $i \in c_n$, $c_n \in c \cap \hat{c}$ *and* $c = \hat{c} \setminus \{c_\ell, c_m\} \cup (c_\ell \cup c_m)$.

*b) Members of coalitions that are not involved in a concentration are better off after the concentration if* $2\chi''^2 > \chi'\chi'''$. *That is,*

$\pi_i(c_n, c) > \pi_i(c_n, \hat{c})$ *for all* $i \in c_n$, $c_n \in c \cap \hat{c}$ *and* $c = \hat{c} \setminus \{c_\ell, c_m\} \cup (c_\ell \cup \{j\}) \cup (c_m \setminus \{j\})$.

Property 4 stresses the free-rider incentive of countries due to the non-excludability of the public good "clean environment". Even if a country does not participate in cooperation (or belongs to a small coalition), it benefits from the higher abatement efforts of other cooperating countries (or countries belonging to larger coalitions). Hence, in any coalition structure different from that comprising only singleton coalitions, a *single* country will be strictly better off. Moreover, the most favorable condition for a single country is if all other countries form one coalition.

## 2.3 First Stage of Coalition Formation

In the first stage of the coalition formation process in which countries choose their membership strategy, we consider two "membership games".

**Simultaneous Move Unanimity Game**

We call the first membership game "simultaneous move unanimity game" to stress similarities and differences to our second game that is called "sequential move unanimity game". The simultaneous move unanimity game is due to Hart and Kurz (1983) which they call Γ-game. In this game, every country i simultaneously announces a list of coalition members. This list contains country i and countries with which country i would like to form a coalition. Countries which have announced the same list form a coalition *if and only if* all members on their list have made exactly the same announcement, otherwise they remain singletons.

For instance, suppose six countries that announce $\ell_1 = \ell_2 = \{1,2\}$, $\ell_3 = \{1,2,3\}$, $\ell_4 = \ell_5 = \{4,5,6\}$ and $\ell_6 = \{6\}$. Then coalition structure c={{1,2},{3},{4},{5},{6}} forms. Country 1 and 2 are in one coalition because they propose the same list and all members on their list make the same proposal. Country 3 remains a singleton: though it would like to form a coalition with country 1 and 2, it is not on their list. Country 4, 5 and 6 also remain singletons. Though country 4 and 5 propose the same list, not all members on their list make the same proposal. Country 6 "intentionally" remains a singleton: country 4 and 5 cannot force country 6 into a coalition.

The example stresses three features of the simultaneous move unanimity game. 1) Participation is voluntary. That is no country can be forced into cooperation. 2) Membership is exclusive. If a country is not on the list of other countries, it cannot join a coalition. 3) Coalitions only form by "strict" unanimity. All three features taken together imply that a high degree of consensus is necessary to form an agreement – an assumption much in line with the problems of "real world" negotiations in international pollution control.

It is evident that in the context of symmetric countries a proposal basically means to announce the size of a coalition of which country i wants to be a member. That is if country i announces a coalition of size $c_\ell$, then there must be $c_\ell - 1$ other countries that also announce $c_\ell$ in order to form coalition $c_\ell$. If there are less than $c_\ell - 1$ other countries, then coalition $c_\ell$ does not form. If there are more than $c_\ell - 1$ other countries that announce $c_\ell$, then $c_\ell$ countries form coalition $c_\ell$ and the remaining countries remain singletons (except if the number of the remaining countries is equal or larger than $c_\ell$ in which case another coalition of size $c_\ell$ may form).

A coalition structure is said to be stable if no single country or no subgroup of countries has an incentive to change its announcement, given the announcement of all other countries. This corresponds to the definition of a strong Nash equilibrium.

### Sequential Move Unanimity Game

The second membership game is due to Bloch (1995) and is called sequential move unanimity game. The game assumes that players (countries) are ordered according to some rule. The country with the lowest index (initiator), say, country 1, starts by announcing a list of coalition members including itself. Every member on the list is asked whether it accepts the proposal. The country with the lowest index on the list is asked first, then the country with the second lowest index and so forth. If all countries agree, the coalition, say, $c_\ell$, is formed and coalitions among the remaining countries $I \backslash c_\ell$ may form. The country with the lowest index among $I \backslash c_\ell$ becomes the new initiator. If a country rejects a proposal, it can make a new proposal. Thus, a coalition only forms by unanimous agreement.

A country deciding whether to accept a proposal by an initiator, i.e., a list of coalition members, will implicitly base its decision on its own list. Hence, as in the simultaneous move unanimity game, coalitions form if and only if lists match. Therefore, also the sequential move unanimity game implies voluntary participation, exclusive membership and strict unanimity. Thus, in this sense, both membership games are identical. However, whereas in the simultaneous move game countries with lists that do not match will become singletons, this does not have to be the case in the sequential move game. Countries of which their proposal has been turned down are still part of the formation process and may become members of other coalitions. Also countries that have turned down a proposal are still part of the game since they can propose a new coalition. Only if N-1 countries have already formed a coalition, country i will have no other choice than to become a singleton.

For simplification, Bloch assumes no discounting. He also assumes that players who cannot agree on a coalition receive a payoff which is Pareto-dominated by payoffs in any coalition structure. Thus, the solution to the game becomes “finite”. Moreover, he only considers stationary perfect equilibrium strategies in order to reduce the amount of possible equilibria.

For symmetric players, Bloch (1996) has shown that things simplify even further since the identity of players does not matter and payoffs to a player only depend on the size of its coalition in a given coalition structure c. Hence, the sequence in which players make proposals and counter-proposals as well as the sequence according to which players are asked for acceptance does not matter for the outcome of this membership game. Moreover, a proposal means to announce the size of a coalition to which the proposer wants to belong. Thus, the game looks as follows. Pick arbitrary some initiator, say, country 1 that proposes a coalition of size $c_\ell \in \{1,\ldots, N\}$. If all countries accept, then coalition $c_\ell$ forms and country $c_\ell+1$ proposes a coalition of size $c_m \in \{1, \ldots, N-c_\ell\}$. This process continues until $\sum_{\ell=1}^{M} c_\ell = N$ in this “size announcement game”.

Bloch (1996) has shown that in the case of symmetric players the set of stationary perfect equilibria in the original sequential move unanimity game coincides with the set of subgame perfect equilibria in the sequential size announcement game. That is, at each time t of the negotiations, an equilibrium proposal must be a best response for the rest of the game.

**Example**

In order to illustrate the determination of equilibrium coalition structures in both membership games, we consider a simple example. This example assumes the following payoff function $\pi_i = \sum_{j=1}^{N} q_j - \frac{1}{2} q_i^2$ which implies dominant strategies. Optimal abatement of country i, being a member of coalition $c_\ell$, is $q_i^*(c_\ell) = c_\ell$. Hence, the payoff to a country in coalition $c_\ell$ in a coalition structure with M coalitions is $\pi_{c_\ell} = \sum_{m=1}^{M} (c_m)^2 - \frac{1}{2}(c_\ell)^2$. Suppose N=4 and hence there are five coalition structures with five valuations:

$c^1=(1,1,1,1)$, $c^2=(2,1,1)$, $c^3=(2,2)$, $c^4=(3,1)$, $c^5=(4)$

$\pi(c^1) = (3.5, 3.5, 3.5, 3.5)$, $\pi(c^2) = (4, 5.5, 5.5)$, $\pi(c^3) = (6, 6)$, $\pi(c^4) = (5.5, 9.5)$, $\pi(c^5) = (8)$.

where we may recall that coalitions are ordered in descending size and payoffs (inversely related to the size of coalitions) in ascending size.

We start by considering strong Nash equilibria in the simultaneous move unanimity game. First note that coalition structures $c^1$, $c^2$ and $c^3$ cannot be equilibria since they are Pareto-

dominated by other coalition structures. Hence, the group of all countries would have an incentive to change their announcement. Second, consider coalition structure $c^4$ and suppose that country 1 to 3 have announced $c_\ell = 3$ and country 4 $c_m = 1$. Clearly, no country has an incentive to change its announcement so that coalition structure $c^1$ or $c^2$ forms. It is also evident that members of coalition $c_\ell = 3$ would prefer a move either to coalition structure $c^3$ or $c^5$ which, however, is not in the interest of country 4. Since both moves require a change of announcements of *all* countries, it is not possible for members of coalition $c_\ell = 3$ to move to $c^3$ or $c^5$ due to the requirement of strict unanimity. Therefore, $c^4$ constitutes a strong Nash equilibrium.
Also $c^5$ is a strong Nash equilibrium that forms if and only if all countries announce $c_\ell = 4$. The only potential challenge is $c^4$. However, if a single country changed its announcement to $c_m = 1$, the remaining coalition of three members would break apart since announcements do not match anymore. This would give only a payoff of 3.5 instead of 8. Hence, $c^5$ is also a strong Nash equilibrium.[8]

For the sequential move unanimity game, the equilibrium selection can be illustrated with the help of a decision tree. In the figure below, numbers attached to a branch represent proposals at time t that are the size of coalitions. The numbers at the end of a branch are the payoffs to countries associated with a coalition structure. Bold faced branches indicate an equilibrium path at time t for the remaining game. For instance, if the initiator proposes a coalition of size 2 at time t=1 (which is accepted in the size announcement game by definition), then at time t=2, a new initiator can propose either a coalition of size 1 or 2. A proposal of size 2 leads to coalition structure $c^3 = (2,2)$ with a payoff of 6 to all countries. A proposal of size 1 implies that the remaining country remains a singleton and hence coalition structure $c^2$=(2,1,1) forms where members of the coalition of size 2 receive a payoff of 4 and the singletons a payoff of 5.5. Hence, given that a coalition of size 2 has been proposed at time t=1, an optimal proposal at time t=2 would be to propose a coalition of size 2 as well.

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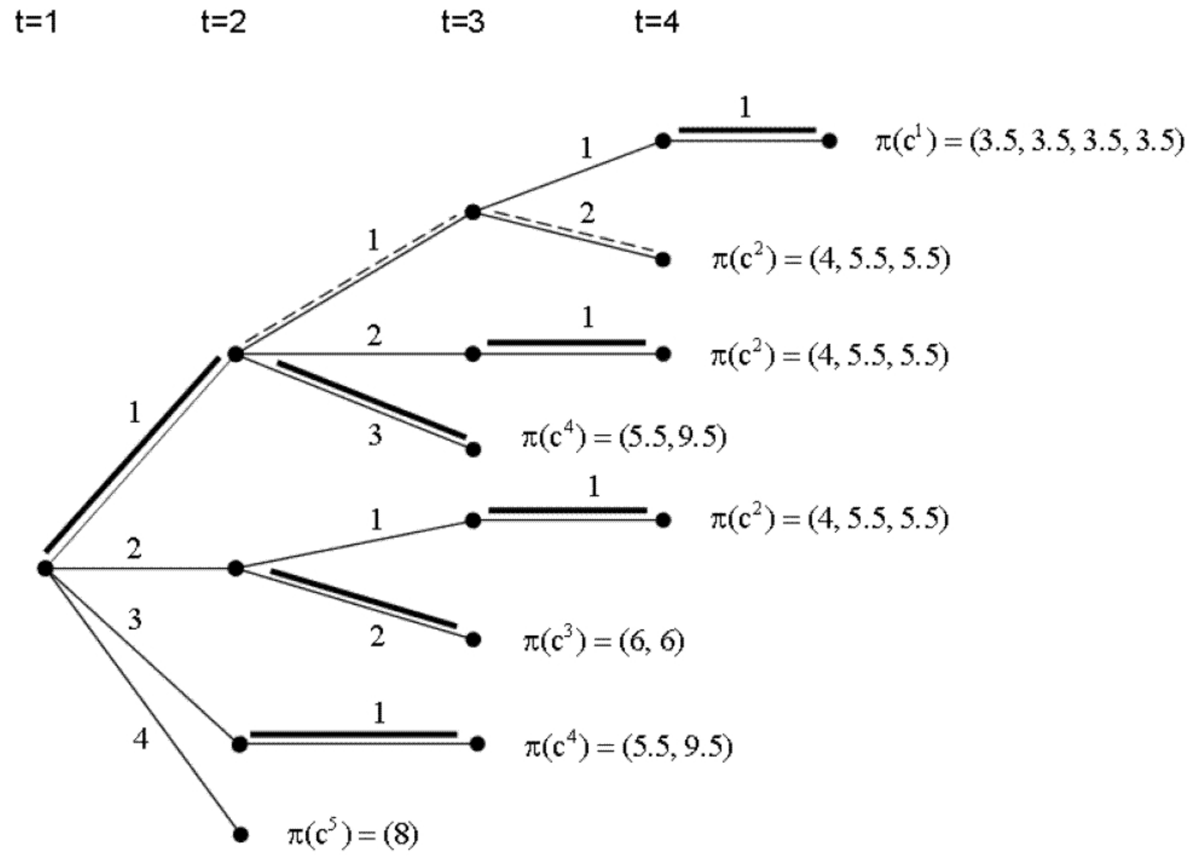
[8] It is evident that in the context of symmetric players the identity of players does not matter for the determination of equilibrium coalition structures. Since this is the primary concern in this and the following section, we will continue to view for instance coalition structure $c^4$ as one equilibrium, though strictly speaking there are four equilibria of the form $c^4$=(3,1). Clearly, it matters for individual payoffs whether a country belongs to coalition 3 or whether it is a singleton. This difference will be considered in section 4 where we analyze the role of a regulator and give up the assumption of exogenously given index numbers.



From the graph, it is evident that if the initiator, say, country 1, proposes a coalition of size 1 at time t=1, country 2 is indifferent between proposing a coalition of size 1 or 3 at t=2. Hence, in order to avoid such knife-edge cases, we follow Ray/Vohra (1999) and assume that in the case of indifference a country proposes the larger coalition.[9] Thus, the equilibrium path from time t=2 onwards is uniquely determined. Thus, country 1 proposing a coalition of size 1, 2, 3 or 4 at time t=1 will earn a payoff of 9.5, 6, 5.5 or 8. Therefore, the initiator will propose a coalition of size 1 and the "second initiator" a coalition of size 3 leading to equilibrium coalition structure $c^4=(3,1)$.[10]

Obviously, in this example, the sequential decision process introduces a strategic option: the initiator can credibly commit to remain a singleton, benefiting from the abatement efforts of the remaining countries and hence the grand coalition will not be a stable outcome of coali-

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[9] In section 3, we show that this assumption ensures that there is always a unique equilibrium. Moreover, we demonstrate that our qualitative conclusions will not be affected if this assumption is modified.

[10] A similar comment as in footnote 8 applies. That is, the identity of players associated with the sequence in which countries make proposals does not matter for the characterization of equilibrium coalition structures as considered in this and the following section, but will be important when analyzing the role of a regulator in section 4.

tion formation. This was different in the simultaneous move game where apart from $c^4$=(3,1) also $c^5$=(4) was stable. Clearly, due to Property 2 and 3, $c^5$ is superior to $c^4$ in terms of global welfare and global emissions.

## 3. Equilibrium Coalition Structures without Regulator

In this section, we determine equilibrium coalition structures in the two membership games and compare them in terms of global abatement and global welfare. That is, we generalize our observations of the simple example from above that ignored the role of a regulator. We restrict attention to payoff functions implying dominant abatement strategies. In section 4, we then consider the influence of a regulator on equilibrium outcomes. In section 5, we show that our main conclusions of previous sections will also hold for payoff functions implying non-dominant strategies.

### 3.1 Simultaneous Move Unanimity Game

For the characterization of equilibrium coalition structures in the simultaneous move unanimity game, it turns out to be helpful to define and characterize Pareto-optimal coalition structures.

**Definition 1: Pareto-optimal Coalition Structures**

*A coalition structure c is Pareto-optimal if there is no other coalition structure* $\hat{c}$ *where at least one country is better off and no country is worse off, i.e.,* $\forall\ \hat{c} \neq c$ *with* $\pi_i(\hat{c}_\ell, \hat{c}) > \pi_i(c_\ell, c)$ *for some i* $\exists\ j \in I : \pi_j(\hat{c}_m, \hat{c}) < \pi_j(c_m, c)$.

Definition 1 implies that there is no other coalition structure $\hat{c}$ which weakly Pareto-dominates c. From Property 3 (“the grand coalition generates the highest global payoff”), it follows that the coalition structure with the grand coalition is Pareto-optimal since any deviation to some other coalition structure will imply a (strict) payoff loss to at least one country. Moreover, symmetric coalition structures of the form $c=(c_1,\ldots,c_1)$ (including the singleton coalition structure) implying symmetric payoffs can never be Pareto-optimal since all countries would be better off in the grand coalition. For payoff functions implying dominant strategies, an even sharper characterization of Pareto-optimal coalition structures is possible.

**Proposition 1: Pareto-optimal Coalition Structures**

*Let the set of Pareto-optimal coalitions for a given number of countries N be denoted by* $C^{PO}(N)$*, then for payoff functions implying dominant abatement strategies:*

$\{(N)\} \subset C^{PO}(N) \subset \{(N)\} \cup \{c = (c_1, \ldots, c_M)\} \,\big|\, M \geq 2,\ c_1 \geq \ldots \geq c_M,\ (c_1, \ldots, c_M) \backslash c_\ell \in C^{PO}(N - c_\ell)$ $\forall\, \ell \in \{1, \ldots, M\},\ \pi_i(c_M, c) > \pi_i(N, (N))\}$.

**Proof:** As pointed out above, $(N) \in C^{PO}(N)$ follows from Property 3. In order to show that $c \in C^{PO}(N)$ implies that $c^S \in C^{PO}(S)\ \forall\, c^S \subset c$ must hold, assume to the contrary that there would exist $c^S, \hat{c}^S \in C^S$, $c = (c^S, \tilde{c}) \in C^{PO}(N)$ and $\hat{c} = (\hat{c}^S, \tilde{c}) \in C$ such that $\hat{c}^S$ weakly Pareto-dominates $c^S$. From $c \in C^{PO}(N)$, it follows: $\exists\, j \in I \backslash S$, $j \in c_m \in \tilde{c}$ such that $\pi_j(c_m, \hat{c}) < \pi_j(c_m, c)$. Hence, $\sum_{i \in S} \hat{q}_i < \sum_{i \in S} q_i$ because $\hat{q}_j = q_j\ \forall\, j \in I \backslash S$ due to dominant abatement strategies. Thus, $\hat{q}_i < q_i\ \forall\, i \in S$ must be true for $\pi_i(\hat{c}_\ell, \hat{c}) \geq \pi_i(c_\ell, c)$, $i \in c_\ell \in c$ and $i \in \hat{c}_\ell \in \hat{c}$. Consequently, $\hat{c}_\ell < c_\ell\ \forall\, i \in S$ from Property 1a (and the assumption of dominant strategies). However, the transition from $c^S$ to $\hat{c}^S$ (implying that coalition structure c changes to $\hat{c}$) leads to a decrease of aggregate benefits ($\Delta B$) which exceeds the decrease of aggregate costs ($\Delta X$) for countries belonging to S:

$$\Delta X = \sum_{i \in S} (\chi(q_i) - \chi(\hat{q}_i)) = \sum_{i \in S} \int_{\hat{q}_i}^{q_i} \chi'(q) dq < \sum_{i \in S} (q_i - \hat{q}_i) \chi'(q_i) = \sum_{i \in S} (q_i - \hat{q}_i) b c_\ell \leq \sum_{i \in S} (q_i - \hat{q}_i) bS$$
$$= Sb \sum_{i \in S} (q_i - \hat{q}_i) = \Delta B .$$

where $\beta' = b$ in the case of linear benefit functions. Hence, $\sum_{i \in S} \pi_i(c_\ell, c) > \sum_{i \in S} \pi_i(\hat{c}_\ell, \hat{c})$ which is a contradiction to the assumption that $\hat{c}^S$ weakly Pareto-dominates $c^S$.

Finally, if $\pi_i(c_M, c) > \pi_i(N, (N))$, then c is not Pareto-dominated by the grand coalition due to Property 1b. **Q.E.D.**

Proposition 1 says that the set of Pareto-optimal coalition structures comprises coalition structures that include the grand coalition and maybe smaller coalitions. In the case of smaller coalitions, necessary conditions are that a) every "subcoalition structure" must be a Pareto-optimal coalition structure itself and b) a coalition structure must not be Pareto-dominated by the grand coalition. Table 1 below lists Pareto-optimal coalition structures for two examples. For instance, in example 1, $C^{PO}(6) = \{(6), (5,1)\}$. (6) is the grand coalition. (5,1) belongs to $C^{PO}(6)$ since (5,1)\(5)=(1) is a Pareto-optimal subcoalition structure (see N=1) as well as (5,1)\(1)=(5) (see N=5) and $\pi_i(1, (5,1)) > \pi_i(6, (6))$. However, (4,2) is (and also other coalition structures are) not Pareto-optimal since $\pi_i(2, (4,2)) \leq \pi_i(6, (6))$ and due to Property 1b, we know that this implies also $\pi_j(4, (4,2)) < \pi_j(6, (6))$.

**Table 1: Pareto-optimal Coalition Structures***

| N | Example 1 | Example 2 | N | Example 1 | Example 2 |
|---|---|---|---|---|---|
| 1 | (1) | (1) | 7 | (7), (6,1), (5,2) | (7), (6,1), (5,2) |
| 2 | (2) | (2) | 8 | (8), (7,1), (6,2) | (8), (7,1), (6,2) |
| 3 | (3) | (3), (2,1) | 9 | (9), (8,1), (7,2) | (9), (8,1), (7,2), (6,3), (6,2,1) |
| 4 | (4), (3,1) | (4), (3,1) | 10 | (10), (9,1), (8,2), (7,3) | (10), (9,1), (8,2), (7,3), (7,2,1), (6,3,1) |
| 5 | (5), (4,1) | (5), (4,1) | 11 | (11), (10,1), (9,2), (8,3) | (11), (10,1), (9,2), (8,3), (8,2,1), (7,3,1) |
| 6 | (6), (5,1) | (6), (5,1), (4,2) | 12 | (12), (11,1), (10,2), (9,3), (8,3,1) | (12), (11,1), (10,2), (9,3), (9,2,1), (8,4), (8,3,1) |

* Example 1 assumes $\pi_i = \sum_{j=1}^{N} q_j - \frac{1}{2} q_i^2$ and example 2 $\pi_i = \sum_{j=1}^{N} q_j - e^{q_i}$ .

We are now equipped to characterize equilibrium coalition structures.

**Proposition 2: Equilibrium Coalition Structures in the Simultaneous Move Unanimity Game**

*Let the set of strong Nash equilibria in the simultaneous move unanimity game for a given number of countries N be denoted by* $C^*(N)$ *and the set of Pareto-optimal coalition structures by* $C^{PO}(N)$*, then for payoff functions implying dominant strategies:* $C^*(N) = C^{PO}(N)$*.*

**Proof:** a) $C^{PO}(N) \subset C^*(N)$: Suppose to the contrary that there is a coalition structure $c \in C^{PO}$ but $c \notin C^*$. Then there exists a set of deviating countries S that can improve the payoff of at least one member without negatively affecting the payoff of other members by deviation to coalition structure $\hat{c}$. Coalition structure c and $\hat{c}$ may be written as $c = (c^S, \tilde{c})$ and $\hat{c} = (\hat{c}^S, \tilde{c})$ where $c^S$ is a subcoalition structure that comprises the set of coalitions which have at least one deviating member. $\tilde{c}$ is the subcoalition structure of the residual countries (if there are any), I\S; $\hat{c}^S$ is the subcoalition structure that comprises the coalitions of S after the deviation and singleton coalitions formed by players $c^S \backslash S$ if $c^S \backslash S \neq \emptyset$. Since the deviators receive at least the same payoff in $\hat{c}$ as in c, the same must be true for the singletons in $\hat{c}^S$ due to Property 1b. Hence, $c^S \notin C^{PO}(S)$ which is a contradiction to the structure of $C^{PO}(N)$ for payoff functions implying dominant abatement strategies (see Proposition 1). Hence, $C^{PO}(N) \subset C^*(N)$.
b) $C^*(N) \subset C^{PO}(N)$: Follows from the fact that every strong Nash equilibrium must be immune against a deviation by all countries (S=I). **Q.E.D.**

Hence, according to Proposition 2, all coalition structures listed for the two examples in Table 1 constitute strong Nash equilibria in the simultaneous move unanimity game.

## 3.2 Sequential Move Unanimity Game

For the characterization of equilibrium coalition structures in the sequential move unanimity, we follow a similar procedure as above. That is, we first define and characterize a particular type of coalition structures that is a Pareto-dominance partition derived from a sequence of Pareto-dominance numbers.

**Definition 2: Pareto-dominance Numbers and Pareto-dominance Partition**

*For a given number of countries N, let the Pareto-dominance numbers in increasing sequence be denoted by* $f=(f_i)_{i\in \mathbb{N}_0}$ *and the Pareto-dominance partition in descending sequence by* $\Phi(N)=\{f^1(N),\ldots,f^M(N)\}=\{f^1,\ldots,f^M\}$*.*

*Then for payoff functions implying dominant abatement strategies,* $\Phi(N)$ *is recursively defined as follows. Fix i:=0 and define* $f_i:=1$ *and* $\Phi(1):=1$*. Let the Pareto dominance partition of N be given by* $\Phi(N)=\{f^1(N),\ldots,f^M(N)\}$, $f^\ell > f^{\ell+1}$ $\forall$ $\ell<M$, $\{f^1,\ldots,f^M\}\subset\{f_0,\ldots,f_i\}$ *where* $f^1=\max\limits_{f_j\le N} f_j$, $f^2=\max\limits_{f_j\le N-f^1} f_j$ *and so on. Then,*

$$\Phi(N+1)=\begin{cases}(f^1(N),\Phi(N+1-f^1(N)) & \textit{if this coalition structure is not weakly Pareto-} \\ & \textit{dominated by the grand coalition} \\ (N+1) & \textit{otherwise}\end{cases}.$$

*If* $\Phi(N+1)=(N+1)$*, then* $i:=i+1$ *and* $f_i:=N+1$*.*

The Pareto-dominance partition of N, $\Phi(N)$, may be interpreted as a coalition structure of players $I\in\{1,\ldots,N\}$ and is called Pareto-dominance coalition structure in the following and denoted by $c^{PD}(N)$. For example 1, in Table 1, assuming $\pi_i=\sum_{j=1}^{N} q_j-\frac{1}{2}q_i^2$, the Pareto-dominance numbers are for instance f=(1, 2, 3, 5, 8, 13, 20, 31, 47, 73, ...). For N=1, $f_1$=1 follows immediately from Definition 2. For N=2, $f_2$=2 because $\pi_i(2,(2))\ge\pi_i(1,(1,1))$ and for N=3, $f_3$=3 because $\pi_i(3,(3))\ge\pi_i(1,(2,1))$. For N=4, $\pi_i(4,(4))<\pi_i(1,(3,1))$ and hence $f_4\ne 4$. However, $\pi_i(5,(5))>\pi_i(2,(3,2))$ for N=5 and hence $f_4=5$. Once the sequence of Pareto-dominance numbers is known up to a given N, the Pareto-dominance partition can simply be derived by choosing the largest Pareto-dominance number smaller or equal to N, i.e., $f^1(N)=\max\limits_{f_j\le N} f_j$. Then one searches for the largest PD-number equal or smaller than N-$f^1$(N) and so on. This process continues until $\Sigma f^i=N$. For instance, suppose N=12. Then, in example 1: $8=f^1=\max\limits_{f_j\le N=12} f_j$, $3=f^2=\max\limits_{f_j\le N=12-8} f_j$, $1=f^3=\max\limits_{f_j\le N=12-8-3} f_j$

and hence $\Phi(12)=\{8,3,1\}$ and $c^{PD}(12)=(8,3,1)$.

For example 2, in Table 1, assuming $\pi_i = \sum_{j=1}^{N} q_j - e^{q_i}$, the sequence of Pareto-dominance numbers is given by f=(1, 2, 4, 7, 11, 18, 29, 46, 74,…). For both examples, the Pareto-dominance coalition structures are displayed in Table 2.

**Table 2: Pareto-dominance Coalition Structures***

| N | Example 1 | Example 2 | N | Example 1 | Example 2 |
|---|---|---|---|---|---|
| 1 | (1) | (1) | 7 | (5,2) | (7) |
| 2 | (2) | (2) | 8 | (8) | (7,1) |
| 3 | (3) | (2,1) | 9 | (8,1) | (7,2) |
| 4 | (3,1) | (4) | 10 | (8,2) | (7,3) |
| 5 | (5) | (4,1) | 11 | (8,3) | (11) |
| 6 | (5,1) | (4,2) | 12 | (8,3,1) | (11,1) |

* Example 1 assumes $\pi_i = \sum_{j=1}^{N} q_j - \frac{1}{2} q_i^2$ and example 2 $\pi_i = \sum_{j=1}^{N} q_j - e^{q_i}$ .

We have now all information to characterize equilibrium coalition structures in the sequential move unanimity game.

**Proposition 3: Equilibrium Coalition Structures in the Sequential Move Unanimity Game**

*Let the unique subgame perfect equilibrium in the sequential move unanimity game for a given number of countries N be denoted by* $c^{**}(N)$ *and the Pareto-dominance coalition structure by* $c^{PD}(N)$*, then for payoff functions implying dominant abatement strategies and cost functions with* $2\chi''^2 > \chi'\chi'''$: $c^{**}(N) = c^{PD}(N)$.

**Proof**: See the Appendix. **Q.E.D.**

Intuitively, in a positive externality game, each country likes to be a member of the smallest coalition due to Property 1 and prefers that the remaining countries form a very coarse or concentrated coalition structure due to Property 4. Thus, a proposer has an incentive to propose a small coalition, however, subject to the constraint that the remaining countries form a stable subcoalition structure. A subcoalition structure (and also the entire coalition structure) is stable if and only if it is an element of a Pareto-dominance partition.

From the two examples in Table 2, it is evident that for some N the grand coalition is an equilibrium coalition structure and for some it is not.

### 3.3 Evaluation

In this subsection, we evaluate our results of the previous two subsections with respect to four items. First, we clarify existence of an equilibrium. For the sequential move unanimity game, existence has been established by Bloch (1996). In fact, in our model, the stable coalition structure is always non-trivial (i.e., a coalition structure with at least one coalition of size larger than one) for $N \geq 2$ since not only $f_1=1$ by definition but also $f_2=2$.[11] For the simultaneous move unanimity game, this follows from the fact that the coalition structure with the grand coalition is always stable and the trivial coalition structure is not Pareto-optimal.

Second, only in the sequential move unanimity game there is a unique equilibrium coalition structure. This is either the case if we rule out payoff functions with indifferent valuations or if we make a behavioral assumption how indifference is resolved. As pointed out in subsection 2.4, we assume in line with Ray/Vohra (1999) that a country proposes the larger coalition in case of indifference. An alternative assumption, though probably less plausible, could be to assume just the opposite. This would lead to different Pareto-dominance numbers and partitions as described in Definition 2, but they would also be unique. For instance, in example 1 in Table 2, the Pareto-dominance numbers would then be given by f=(1, 2, 4, 7, ….) and hence $c^{**}(1)=(1)$, $c^{**}(2)=(2)$, $c^{**}(3)=(2,1)$, $c^{**}(4)=(4)$, $c^{**}(5)=(4,1)$, $c^{**}(6)=(4,2)$ and $c^{**}(7)=(7)$. Hence, our conclusion that in the sequential move unanimity game the coalition structure with the grand coalition may not be stable for some N would still be valid.

Third, equilibrium coalition structures in both games constitute a Pareto-improvement to all countries and global abatement will be higher compared to the coalition structure comprising only of singleton coalitions. The claim about Pareto-improvement that we may also call profitability follows from two facts. a) Countries that are singletons receive a strictly higher payoff in any coalition structure different from the trivial coalition structure due to positive externalities (Property 4). b) Therefore, in case profitability would be violated for some countries that are members of a non-trivial coalition, these countries would simply leave their coalition in the simultaneous move unanimity game. In the sequential move unanimity game, these countries would neither make such proposal nor would they accept it. Thus, profitability is a necessary condition for a coalition structure to be stable in both membership games in the presence of positive externalities. The claim about global abatement follows from the fact that only non-trivial coalition structures are stable. Since any non-trivial coalition structure is coarser than the trivial coalition structure, Property 2a applies.

Fourth and most important, the coarsest equilibrium coalition structure in the simultaneous move unanimity game is at least as coarse as in the sequential move unanimity game. This follows immediately from Proposition 2 and 3. Since in the simultaneous move unanimity

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[11] For N=2, $\pi_i(2,(2)) > \pi_i(1,(1,1))$ for any payoff function by Property 3.

game the coalition structure with the grand coalition is always stable, a sequential coalition formation process may lead to an inferior outcome in terms of global welfare (Property 3) and global abatement (Property 2). In other words, a sequential decision about membership opens up the opportunity of strategic behavior that may have a negative global effect. However, the grand coalition is only one equilibrium among many other equilibria in the simultaneous move unanimity game. Hence, without any coordination, it is not self-evident whether the grand coalition will actually emerge as an outcome.

## 4. Equilibrium Coalition Structures with Regulator

Consistent with our previous assumption, we assume that a regulator can only make recommendations to the various parties, but cannot enforce an international environmental agreement. That is, the regulator can only assume the role of a coordinator or moderator. In the simultaneous move unanimity game, this means that the regulator can propose an equilibrium or more generally, a probability distribution over the play of equilibrium coalition structures. Since in the sequential move unanimity game, equilibrium coalition structures follow from the index of players, which in turn determine the sequence in which countries can make proposals, the regulator proposes a probability distribution over all possible index sequences of players. For a given proposal, this leads to expected payoffs with regulator.

We assume that the regulators aim is to maximize the sum of expected payoffs to all players. However, his recommendation faces the restriction that all participants have to accept his proposal. That is, the expected payoff to each participant must me at least as high as without regulator in which case nature draws a probability distribution.

More formally, let $R = \{r_1, ..., r_M\}$ be the set of equilibrium coalition structures in the simultaneous move unanimity game and the set of possible index sequences (i.e., the set of permutations of the set of players I) in the sequential move unanimity game.[12] That is, R is the set of pure strategies. The payoff vector $\upsilon = (\upsilon_1, ..., \upsilon_N)$ is given by

$\upsilon(r_j) := \pi(r_j)$ in the simultaneous move unanimity game and by

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[12] For instance, suppose six players. Then, there are 720 permutations and hence 720 possible sequences in which players can move in the sequential move unanimity game. In the simultaneous move game, there would be 7 equilibria in example 1 and 22 in example 2 according to Table 1, noticing that coalition structure (5,1) means 6 and coalition structure (4,2) 15 different equilibria.

$\upsilon(r_j) := \frac{1}{\left|C^*(r_j)\right|} \sum_{c \in C^*(r_j)} \pi(c)$ in the sequential move unanimity game

with $C^*(r_j)$ the set of equilibrium coalition structures given index sequence $r_j$. Let the regulator propose a mixed strategy $p_R^* = (p_{r_1}^*, ..., p_{r_M}^*)$ that is a probability distribution over R and let $z_R = (z_{r_1}, ..., z_{r_M})$ with $\sum_{r_j \in R} z_{r_j} = 1$ and $z_{r_j} > 0 \;\; \forall\, r_j \in R$ be the probability distribution of nature, then $p_R^*$ solves the regulators maximization task:

$$p_R^* = \arg\max \sum_{i \in I} \sum_{j=1..M} p_{r_j} \upsilon_i(r_j)$$

[4]

$$\text{s.t.: } \sum_{j=1..M} p_{r_j} \upsilon_i(r_j) \geq \sum_{j=1..M} z_{r_j} \upsilon_i(r_j) \; \forall\, i \in I \; .$$

We note that, generally, the solution to the regulators problem may not be unique. However, there exist at least one solution since, trivially, the regulator can always propose $p_R = z_R$. Of course, this would imply no improvement compared to nature. Thus, the question arises under which conditions the regulator can improve upon nature. The following statement provides a general answer.

**Proposition 4: Pareto-Improvement Through Regulator**

*Let the payoff space of the regulator be given by* $V(R) :=$ *convex hull of* $\left\{ \upsilon(r_j) \middle| r_j \in R \right\}$ *and let the Pareto-frontier of V(R) be denoted by PO(V(R)) where the dimension of these spaces are denoted by dimV(R) and dimPO(V(R)), respectively. Moreover, let* $P_R^*$ *be the set of probability distributions over pure strategies R that solve the maximization task of the regulator in [4]. Then, the regulator can strictly improve upon the situation without regulation (i.e.,* $\sum_{j=1..M} p_{r_j}^* \upsilon_i(r_j) > \sum_{j=1..M} z_{r_j} \upsilon_i(r_j) \;\; \forall\, p_R^* \in P_R^* \;\; \forall\, i \in I$ *) if and only if*

*a) dimV(R)=N or*

*b) dim PO(V(R))<dimV(R)<N.*

**Proof:** Under a) and b) dimPO(V(R))<dimV(R) holds. Hence, every strict convex combination of the M points $\upsilon(r_j)$, $r_j \in R$, lies in the interior of V(R) and therefore not on the Pareto-frontier. Note that because $z_{r_j} > 0 \;\; \forall\, r_j \in R$, $\sum_{j=1..M} z_{r_j} \upsilon(r_j)$ is such a strict convex combination. Hence, the regulator can increase the payoff to all players by proposing a probability distribution different from nature. However, if dimPO(V(R))=dimV(R), then $\sum_{j=1..M} z_{r_j} \upsilon(r_j)$ lies on the Pareto-frontier. Therefore, any proposal different from nature would imply a violation of least one constraint in [4]. **Q.E.D.**

In order to relate Proposition 4 to our previous results and in particular to the two membership games, we now introduce our assumption of symmetric players. In this context, and without any other "external information", it seems suggestive (though not necessary for the proof of Proposition 5 below!) to assume for nature an equal distribution, i.e., $z_{r_j} = 1/M \ \ \forall\, r_j \in R$. In the case of the sequential move unanimity game, this would imply that every index sequence is equally likely. That is, the likelihood of enjoying a first (second and so on) mover advantage (or disadvantage) would be the same for all players. This would imply that every player is equally likely to enjoy the payoff of being a member in a smaller coalition or to have the disadvantage of being a member in a larger coalition in a given (asymmetric) equilibrium coalition structure (see footnote 12). The last remark directly carries over to the simultaneous move unanimity game. Note that this assumption would also imply an equal treatment rule of symmetric players so that all players receive the same expected payoff.

**Proposition 5: The Impact of the Regulator in the Simultaneous and Sequential Move Unanimity Game**

*Suppose all players* $i \in I$ *are symmetric and assume payoff functions implying dominant strategies. Then, the following relations hold.*

*a) In the simultaneous move unanimity game, the regulator can strictly raise the expected global payoff compared to the situation without regulator if* $(N-1,1)$ *is a Pareto-optimal coalition structure.*

*b) In the sequential move unanimity game, the regulator cannot improve upon the situation without regulator.*

**Proof:** a) We show that the assumption of Proposition 4 holds. From Proposition 1 and 2 it follows that i) $(N) \in C^{PO}(N) = C^{*}(N)$ is always true and ii) provided $(N-1,1)$ is a Pareto-optimal coalition structure also $(N-1,1) \in C^{PO}(N) = C^{*}(N)$ holds. Consequently, there are at least N+1 equilibrium coalition structures. The associated payoffs take the form $v_0 = (b,b,b,...,b)$, $v_1 = (a,c,c,....,c)$, $v_2 = (c,a,c,...,c)$, $v_3 = (c,c,a,....,c)$, ..., $v_N =$ (c,c,...,c,a) with a>b>c. Since the N vectors $v_1 - v_0 = (a-b, c-b, ...., c-b)$, $v_2 - v_0 = (c-b, a-b, ...., c-b)$, ..., $v_N - v_0 = (c-b, c-b, ...., a-b)$ are linearly independent, they set up a space of dimension N, with origin $v_0$.

b) From Proposition 3, it follows that equilibrium coalition structures are unique, except for the permutation of the set of players I. Since all permutations lead to the same global payoff for symmetric players, all payoffs lie on the Pareto-frontier. Hence, dimV(R)= dimPO(V(R)) and Proposition 4 applies. **Q.E.D.**

Proposition 5 implies that the regulator′s solution to [4] is unique and he will propose with probability one the grand coalition in the simultaneous move unanimity game. No country will raise objections against this proposal and global welfare is maximized (according to Property 3) and global emissions are minimized (according to Property 2). Apart from this, the regulator solves the problem of multiple equilibria in this game. In contrast, in the sequential move unanimity game, the regulator cannot exercise his task as moderator or coordinator in the interest of the global good. (The unique solution to [4] is to propose the probability distribution of nature.) Thus, our tentative conclusion in section 3 that a simultaneous formation process *may* lead to superior outcomes compared to a sequential process can now be replaced by a clear-cut conclusion in the context of a regulator.

Viewing all results together suggests that the regulator will be successful in proposing that all countries should announce their membership simultaneously, allowing him to coordinate the formation process since this generates the highest expected payoff to all. Overall, the results stress that even if a regulator is not equipped with enforcement power, he can play an important role in international environmental agreements.

## 5. Extension

In this section, we discuss payoff functions that imply non-dominant abatement strategies. This introduces some complexity for the characterization of equilibrium coalition structures without regulator as carried out in section 3. Nevertheless, it is possible to show that our main result there still holds, namely that the equilibrium with the highest global welfare in the sequential move unanimity maybe globally inferior to that in the simultaneous move unanimity game but not vice versa.

In the simultaneous move unanimity game, it is evident that $C^* \subset C^{PO}$ must still hold, otherwise a deviation by all countries would be beneficial. However, $C^{PO} \subset C^*$ does not necessarily have to be true anymore, as the example below will confirm. Nevertheless, it is possible to show that the coalition structure with the grand coalition is always a strong Nash equilibrium.

**Proposition 6: Equilibrium Coalition Structure in the Simultaneous Move Unanimity Game**

*The coalition structure with the grand coalition is a strong Nash equilibrium in the simultaneous move unanimity game.*

**Proof:** A deviation by a group of countries S from the grand coalition leads to a coalition structure $c = (c_1, ..., c_M)$ with $c_1 \geq ... \geq c_M$ and $c_{M-(N-S)+1} = ... = c_M = 1$ if $S < N$. Since

$N\pi_i(N,N) > c_1\pi_i(c_1,c) + ... + c_M\pi_j(c_M,c)$ by Property 3 and $\pi_i(c_1,c) < \pi_j(c_\ell,c)$ $\forall \ell = 2,$ ..., M , by Property 1b, the deviating countries that form $c_1$ are worse off. **Q.E.D.**

Due to Proposition 6, it is sufficient for the support of our main result to find an example where the coalition structure with the grand coalition is not an equilibrium coalition structure in the sequential move unanimity game. This is shown in Table 3 below which assumes a payoff function as for instance in Barrett (1994) and in many other papers on international environmental agreements.

**Table 3: Equilibrium Coalition Structures***

| Coalition Structure | Payoffs | Global Welfare | Global Abatement | $C^{PR}$ | $C^{PO}$ | $C^{*}$ | $C^{**}$ |
|---|---|---|---|---|---|---|---|
| (1,1,1,1,1) | 47.22, 47.22, 47.22, 47.22, 47.22 | 236.1 | 8.3 | X | | | |
| (2,1,1,1) | 46.09, 48.44, 48.44, 48.44 | 237.5 | 8.8 | | X | | |
| (2,2,1) | 47.50, 47.50, 49.00 | 239.0 | 9.0 | X | X | | |
| (3,1,1) | 46.53, 49.31, 49.31 | 238.2 | 9.2 | | X | | |
| (3,2) | 47.45, 48.72 | 239.8 | 9.3 | X | X | | |
| (4,1) | 47.38, 49.69 | 239.2 | 9.4 | X | X | X | X |
| (5) | 48.08 | 240.4 | 9.6 | X | X | X | |

* The example assumes $\pi_i = b\left(a\sum_{j=1}^{N} q_j - \frac{1}{2}(\sum_{j=1}^{N} q_j)^2\right) - \frac{1}{2}c(q_i)^2$ , a=10, b=1, c=1 and N=5. $C^{PR}$ , $C^{PO}$, $C^{*}$ and $C^{**}$ denote the set of coalition structures which are (weakly) profitable, Pareto-optimal, constitute a strong Nash equilibrium in the simultaneous move unanimity game and constitute a subgame perfect equilibrium in the sequential move unanimity game, respectively.

It is evident from Proposition 6 that the issues of existence of equilibrium and Pareto-improvement together with conclusions about global abatement discussed in subsection 3.3 directly carry over to non-dominant strategies in the case of the simultaneous move unanimity game. In the case of the sequential move unanimity game, they also hold. Only in terms of Pareto-improvement the relation may not be "strict". That is, we cannot rule out that the trivial coalition structure may be stable, though this is not the case in the example above.

Also our main results and conclusions with regulation in section 4 still hold. Proposition 4 (as a preparation for Proposition 5) was a general statement anyway. Moreover, Proposition 5 is also valid with minor changes. For the simultaneous move unanimity game, we have not only to require that (N-1, 1) is a Pareto-optimal coalition structure in Proposition 5a, but also that it is an equilibrium as this is the case in the example in Table 3. For the sequential move unanimity game, the proof of Proposition 5b has to be slightly modified. Since we do not know any longer that the equilibrium is unique (except for the permutation of the set of players I), we have to argue now that expected payoffs are unique by definition. Obviously, with these changes, all conclusions derived after Proposition 5 will also be true here.

## 6. Summary and Concluding Remarks

We modeled the formation of international environmental agreements as a two-stage game in which countries decide in the first stage on their membership and in the second they choose their abatement level. The analysis assumed symmetric countries, focused on the first stage of coalition formation and considered two membership games that share the features a) voluntary participation, b) exclusive membership and c) unanimous agreement about participation but differ in the timing of participation decisions. We showed that in the simultaneous move unanimity game, equilibrium coalition structures are Pareto-optimal and include the grand coalition. In contrast, in the sequential move unanimity game, equilibrium coalition structures must not be Pareto-optimal and the grand coalition may not be stable. We concluded that a sequential decision process makes it easier for countries to commit to low abatement and to free-ride on higher abatement efforts of other countries. This strategic behavior translated not only into lower global abatement but also into lower global welfare. A wider interpretation of this result is that a short time window for negotiations is conducive for the outcome of environmental treaties.

We then analyzed the role of a regulator that has no enforcement power but who can give recommendations to the parties involved in the coalition formation process. We argued that the parties will only accept a proposal if it constitutes a Pareto-improvement to all parties. It became evident that the regulator can improve the situation in the simultaneous move unanimity game, raising the global expected payoff. In the sequential move unanimity game this was not possible. Nevertheless, it should be possible for the regulator to convince all parties to agree on a simultaneous decision process about membership that is coordinated by him. Overall, the results stressed the importance of international organizations in preparing and shaping international environmental treaties. Moreover, it became evident that issues of regulation should not be ignored in future research on international environmental problems despite the fundamental assumption and restriction that IEAs must be self-enforcing.

For future research, we would like to suggest two issues of certainly many other. First, both membership games require unanimity about participation which may be regarded as a too strong assumption. An alternative could be majority voting. However, this would require to set up two new membership games since – to the best of our knowledge - no pair of a simultaneous and sequential move game with this feature exists so far. We expect that this will lead to less positive predictions about the outcome of coalition formation but that the relative superiority of a simultaneous over a sequential decision process remains. Second, the analysis should be extended to heterogeneous countries, though this will introduce a couple of complications. For instance, this means either searching for plausible criteria for the sequence in which countries make proposals or - even more demanding but also more plausible - endogenizing this sequence by making it part of the bargaining game itself. Moreover, heterogeneous countries will require to endogenize the choice of abatement targets and compensation payments since coalitional and individual rationality do no longer automatically coincide. For the solution of these complications, much conceptual work will be needed along the lines proposed for instance by Maskin (2003) and Ray/Vohra (1999). This will also be true for the role of a regulator who may then not only influence participation decisions as assumed in this paper but also those on abatement targets and compensation payments. This seems to be a promising route for future research - a route with not many footprints so far.

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## Appendix: Proof of Proposition 2

*Induction Base*

For N=1, we have $\Phi(1)=\{1\}=c^{**}$.

*Induction Hypothesis*

For all $m<N, c^{**}(m)=\Phi(m)$. Due to Property 1, the first initiator will propose $f^M$ (and the second $f^{M-1}$ and so on), where $\Phi(m)=\{f^1,...,f^M\}$ and $f^\ell > f^{\ell+1}$ $\forall$ $\ell$<M.

*Induction Step*

Demonstrate that $c^{**}(N)=\Phi(N)$ where $\Phi(N)=\{f^1,...,f^M\}$ with $f^\ell > f^{\ell+1}$ $\forall$ $\ell$<M is the Pareto-dominance partition derived from the algorithm described in Definition 2.

*Note*

In order to demonstrate this, we have to show that country 1 proposes $f^M$. Then the induction hypothesis can be applied to the remaining countries where these countries form coalitions according to the partition $\Phi(N-f^M)=\Phi(N)\setminus\{f^M\}$. Recall for payoff functions implying dominant strategies if $f^M$ countries have left the game, the game is the same as it would be played among $N-f^M$ countries: the optimal abatement level of coalition $c_\ell$ is independent of the choice of other coalitions $c\setminus c_\ell$.

*Proof*

To show that country 1 proposes $f^M$, suppose the opposite, namely, that it proposes $\tilde{c}\neq f^M$.

### Case 1: $\tilde{c}=N>f^M$

In order for $\tilde{c}>f^M$ to be possible, $f^M<N$ must be true. That is, the Pareto-dominance partition of N comprises at least two elements. According to the definition of a Pareto-dominance

partition, it is not (weakly) Pareto-dominated by the grand coalition. Hence, $\pi_1(N,(N)) < \pi_1(f^M,\Phi(N))$ due to Property 1b. Then, however, the initiator proposes $f^M$ instead of N. (Suppose Example [1] in Table 2 and N=11. Then, the equilibrium coalition structure is $c^{**} = (8,3)$. In contrast, suppose $\tilde{c} = 11$ instead, then $\pi_1(11,(11)) < \pi_1(3,(8,3))$.)

**Case 2: $f^M < \tilde{c} < N$**

If it was an equilibrium strategy to propose $\tilde{c}$, it would be accepted and the equilibrium coalition structure would be given by $\{\Phi(N-\tilde{c}),\tilde{c}\}$.

**Case 2.1:** $\tilde{c} \in \Phi(N)$

Due to $\tilde{c} \in \Phi(N)$, we have $\{\Phi(N-\tilde{c}),\tilde{c}\}$=$\Phi(N)$. Hence, $\pi_1(\tilde{c},\{\Phi(N-\tilde{c}),\tilde{c}\}) < \pi_1(f^M,\Phi(N))$ follows from Property 1b. That is, it does not pay country 1 to propose a larger coalition if the final coalition structure will contain a smaller one. (Suppose Example [1] in Table 2 and N=19 where $c^{**}$={13,5,1}. In contrast, suppose proposal $\tilde{c} = 5$ instead, then $\pi_1(5,(13,5,1))<$ $\pi_1(1,(13,5,1))$.)

**Case 2.2: $\tilde{c} \notin \Phi(N)$**

Country 1 is worse off by proposing $\tilde{c}$ instead of $f^M$ since a) $\tilde{c} > f^M$ and b) $\Phi(N)$ is more concentrated than $\{\Phi(N-\tilde{c}),\tilde{c}\}$. That is, country 1 would a) be a member of a larger coalition and, additionally, b) the resulting coalition structure would be less concentrated. From a) and Property 1a (assuming dominant abatement strategies) it follows that individual abatement of country 1 would increase, whereas from b) and Property 2b it follows that global abatement decreases. The fact that $\{\Phi(N-\tilde{c}),\tilde{c}\}$ is less concentrated than $\Phi(N)$ is simply an implication of the definition of $\Phi(N)$ (see Definition 2). (Suppose example 1 in Table 2 and N=19 where $c^{**}$={13,5,1}. In contrast, suppose proposal $\tilde{c} = 4$ instead, then c=(Φ(15),4)=(13,2,4) but $\pi_1(1,(13,5,1))>\pi_1(4,(13,2,4))$ Alternatively, suppose proposal $\tilde{c} = 3$, then c=(13,3,3) but $\pi_1(1,(13,5,1))>\pi_1(3,(13,3,3))$.)

**Case 3: $\tilde{c} < f^M$**

First note that $\Phi(\tilde{c}) = \{\tilde{c}\}$ and $f^M = N$, otherwise the proposal $\tilde{c}$ cannot be an equilibrium due to the induction hypothesis. If it was an equilibrium strategy to propose $\tilde{c}$, it would be accepted and the equilibrium coalition structure would be given by $c = \{\Phi(N-\tilde{c}),\tilde{c}\}$. Let $\hat{c}$ be the most concentrated decomposition of Pareto-dominance numbers smaller than $f^M$ and $\hat{f}$ be the smallest element of $\hat{c}$. i) If $\tilde{c} \in \hat{c}$, then $c = \hat{c}$ and $\pi_i(\tilde{c},c) \le \pi_i(N,(N))$ follows from Definition 2 and Property 1b. ii) If $\tilde{c} \notin \hat{c}$ and $\tilde{c} < \hat{f}$, then $\tilde{c}$ cannot be an equilibrium proposal due to the induction hypothesis. iii) If $\tilde{c} \notin \hat{c}$ and $\tilde{c} > \hat{f}$, then $\pi_i(\tilde{c},c) \le \pi_i(\hat{f},\hat{c}) \le \pi_i(N,(N))$ where the first inequality sign follows from Properties 1a (and the assumption of dominant strategies) and 2b. i) Assume N=3 where $c^{**} = (3)$ and proposal $\tilde{c} = 1$ instead, then $\pi_i(1,(2,1)) \leq \pi_i(3,(3))$. ii) Assume N=8 where $c^{**} = (8)$ and $\tilde{c} = 1$, then $\tilde{c} = 1 \notin \hat{c} = (5,3)$. Due to the induction hypothesis, c=(5,2,1) cannot be an equilibrium since it is dominated by $\hat{c}$. iii) Assume N=8 and $\tilde{c} = 4$, then $\tilde{c} \notin \hat{c} = (5,3)$, $\tilde{c} > \hat{f} = 3$ and c=(4,3,1). Then $\pi_i(4,(4,3,1)) \leq \pi_i(3,(5,3)) \leq \pi_i(8,(8))$ (**Q.E.D.**)

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