BEYOND KYOTO.
A GAME-THEORETIC PERSPECTIVE

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Abstract

Since the framework convention of Rio, actual environmental negotiations on climate change aim at inducing all world countries to sign a global environmental agreements to reduce greenhouse gas emissions. In Kyoto, a subset of countries agreed on emission reduction targets, but they are still negotiating on the way to induce the non-signatories to sign the protocol. This paper shows from a game-theoretic viewpoint that the emergence of agreements signed by all countries is quite unlikely, even in the presence of appropriate and multi-issues negotiation strategies and transfers. If countries are non-myopic, the best we can expect is a coalition structure in which multiple regional environmental agreements to control climate change are signed.

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1. Introduction

Climate change is one of the major environmental concern of most countries in the world. Negotiations to control potential climate changes have been taking place, from Rio to Kyoto, for the last five years. There is a widespread consciousness that the risk of incurring in relevant economic and environmental losses due to climate change is high. Scientific analyses have become more and more precise on the likely impacts of climate change. According to the Second Assessment Report of the Intergovernmental Panel on Climate Change, current trends in GHG emissions may indeed cause the average global temperature to increase by 1-3,5 degrees C over the next 100 years. As a result, sea levels are expected to rise by 15 to 95 cm and climate zones to shift towards the poles by 150 to 550 km in mid latitudes. In order to mitigate the adverse effects of climate change, the IPCC report concludes that a stabilisation of atmospheric concentration of carbon dioxide—one of the major GHG—at 550 parts per million by volume (ppmv) is recommended. This would imply a reduction of global emissions of about 50 per cent with respect to current levels.

In this context, countries are negotiating to achieve a world-wide agreement on GHG emissions control in order to stabilise climate changes. Despite the agreement on targets achieved in Kyoto, still many issues remain unresolved. First, the protocol is not yet ratified, and ratification depends on the way policies are going to be designed to achieve the Kyoto targets (e.g. the role of flexible instruments). Second, the protocol has to be implemented, and legal and economic issues, including monitoring and reporting, compliance and sanctions, have to be discussed. Third, it is clear that the Kyoto protocol is only a first important step to keep under control GHGs concentrations and that most of the work has yet to be done. In particular, it crucial to negotiate:

– on targets beyond the year 2012;
– on the way in which countries which did not sign the Kyoto protocol, mostly developing countries and LDCs, can set credible and effective targets, thus joining the group of signatories.

This latter issue can be called the “enlargement issue” and is the focus of the analysis carried out in this paper. No global agreement on climate is indeed going to be environmental effective in the next 50 years without the involvement of many of the countries which did not sign the Kyoto protocol (besides the fact that this is one of the major obstacle preventing US from ratifying Kyoto). Hence, it is crucial to analyse whether there exist the conditions for an agreement on climate change to be signed by all or almost all world countries.

In order to understand whether or not the future beyond Kyoto is likely to be characterised by an increasing number of signatories of the protocol, let us re-call some of the basic features of international negotiations on climate change control. These can be summarised as follows:

- all world countries are involved and required to take a decision on whether or not to sign a protocol with important implications on their energy—and economic—policies;
- no supra-national authority can enforce such a protocol which must therefore be signed on a voluntary basis;
- no commitment to cooperation is likely to be credible. Only positive economic net benefits, which may include environmental benefits, can lead countries to adhere to an international agreement on climate change control;

- climate is a public good. As a consequence all countries are going to benefit from the action taken by a subgroup of one or more countries. There is therefore a strong incentive to free-ride;
- parties involved in the negotiations seem to be conscious that an agreement signed by all world countries is not likely and that the effort of GHG emission abatement has to be concentrated on a sub-group of (more developed) countries. This is indeed the outcome of Kyoto but, as said above, it is necessary to enlarge the number of signatories. Is this possible? How?

The goal of this paper is to analyse the incentives that countries have to sign an international agreement on climate change control. Starting from the basic features of the climate change problem, we discuss under what conditions on the number of countries, the damaging effects of free-riding, the structure of costs and benefits, a coalition, i.e. a group of signatories of the international agreement, can emerge. We will consider two main cases:

(i) environmental negotiations focus on a single agreement which countries are free to sign or not;

(ii) environmental negotiations are designed in such a way that countries can either sign a global agreement or, if more profitable, a set of regional agreements (in a way that mimics the formation of trade blocs).

The paper shows that, despite the public good nature of climate, a coalition is going to form endogenously, i.e. a group of countries, but not all countries, has the incentive to sign the agreement. However, when countries are free to choose, they prefer to agree on the formation of several regional agreements, rather than on the design of a single global agreement. This may be a relevant input for current negotiations on climate control.

The structure of the paper is as follows. In Section 2 we provide the necessary definitions and assumptions. Section 3 determines the equilibrium of the environmental game and analyse its implications. Section 4 analyse the possibility to increase the number of signatories either through a system of transfers or through the linkage of environmental negotiations to other international negotiations. Finally, section 5 analyses the equilibrium outcome when countries are free to sign more than one agreement (regional agreements may emerge). A concluding section proposes directions for further research.

2. Assumptions and Definitions

Assume negotiations take place among n countries, $n \geq 3$, each indexed by $i=1, ..., n$. Countries facing an international environmental problem play a two-stage game. In the first stage—the coalition game—they decide non cooperatively whether or not to sign the agreement (i.e. to join the coalition c of cooperating countries). In the second stage, they play the non cooperative Nash emission game, where the countries which signed the agreement play as a single player and divide the resulting payoff according to a given burden-sharing rule (any of the rules derived from cooperative game theory).[1]

[1] This approach has to be contrasted with the traditional co-operative game approach (e.g. Chander-Tulkens, 1993, 1995) and with a repeated game approach (Barrett, 1994, 1997b). Moreover, notice that the regulatory approach often proposed in public economics is not appropriate given the lack of a supranational authority.

This two stage game can be represented as a *game in normal form* denoted by $\Gamma = (N, \{X_i\}_{i\in N}, \{u_i\}_{i\in N})$, where N is a finite set of players, X_i the strategy set of player i and u_i the payoff function of player i, assigning to each profile of strategies a real number, i.e. $u_i : \Pi_{i\in N} X_i \rightarrow R$. The payoff function is a twice continuously differentiable function.

A *coalition* is any non-empty subset of N. A *coalition structure* $\pi = \{C_1, C_2, \ldots, C_m\}$ is a partition of the player set N, i.e. $C_i \bigcap C_j = \varnothing$ for $i \neq j$ and $\bigcup_{i=1}^{m} C_i = N$.

Since the formation of a coalition creates externalities, the appropriate framework to deal with this game is a *game in partition function form*, in which the payoff of each player depends on the entire coalition structure to which he belongs (Bloch, 1997; Ray and Vohra, 1996). This is why we convert the game in normal form into a game in partition function.

Denote by Π the set of all feasible coalition structures. A *partition function* P: $\Pi \rightarrow R$ is a mapping which associates to each coalition structure π a vector in $\Re^{|\pi|}$, representing the worth of all coalitions in π. In particular, $P(C_i; \pi)$ assigns to each coalition C_i in a coalition structure π a worth. When the rule of payoff division among coalition members is fixed, the description of gains from co-operation is done by a *per-member partition function* p: $\Pi \rightarrow \Re^n$, a mapping which associates to each coalition structure π a vector of individual payoffs in $\Re^n$. In particular $p(C_i; \pi)$ represents the payoff of a player belonging to the coalition C_i in the coalition structure π [2].

Under suitable assumptions (A.2 and A.3 below), the second stage of the game can be reduced to a partition function (Yi, 1997; Bloch 1997). Therefore, the study of coalition formation consists of the study of the first stage of the game, i.e. the negotiation process between the players. This negotiation process can be modelled either as a simultaneous game, in which all the players announce at the same time their strategic choice, or as a sequential one, in which each player can announce his strategy according to an exogenous rule of order. Here we assume that:

A.1. All countries decide <u>simultaneously</u> in both stages;[3]
A.2. The second stage emission game has a <u>unique</u> Nash equilibrium for any coalition structure.

This assumption is necessary for the second stage of the game to be reduced to a partition function. However, in order to convert the strategic form into a partition function, the competition among the various coalitions has also to be specified. The common and perhaps the most natural assumption is that:

A.3. Inside each coalition, players act cooperatively in order to maximise the coalitional surplus, whereas coalitions (and singletons) compete with one another in a non cooperative way.

The partition function is then obtained as a Nash equilibrium payoff of the game played by coalitions and singletons. Formally, for a fixed coalition structure $\pi = \{C_1, C_2, \ldots, C_m\}$, let x^* be a vector of strategies such that

$$\forall C_i \in \pi, \quad \sum_{j\in C_i} u_j\left(x^*_{C_i}, x^*_{N\setminus C_i}\right) \geq \sum_{j\in C_i} u_j\left(x_{C_i}, x^*_{N\setminus C_i}\right) \qquad \forall x_{C_i} \in \times_{j\in C_i} X_j$$

Then define:

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2 Bloch (1997) denotes the per-member partition function by the term “valuation”.

3 By contrast, Barrett (1994) assumes that the group of signatories is Stackelberg leader with respect to non-signatories in the second stage emission game. In Bloch (1997) it is assumed that countries play sequentially in the first stage coalition game.

$$P(C_i;\pi) = \sum_{j\in C_i} u_j\left(x^*\right)$$

Studying the issue of coalition formation by partition function games implies a limitation. The second-stage "reduction" procedure imposes that the grand-coalition satisfies superadditivity, in the sense that the grand coalition should be able to achieve in terms of aggregate worth at least the sum of what is achievable under any coalition structure (Ray and Vohra, 1996, 1997; Bloch, 1997). Indeed, whichever strategies chosen by the coalitions of any coalition structure can be replicated by the grand coalition. The superadditivity concerns just the grand coalition and it is not implied at the level of sub-coalitions, because of the presence of spillovers. This means that in any game of coalition formation, the grand coalition is always an efficient outcome whereas a fragmented coalition structure always results an inefficient outcome.

In order to simplify the derivation of the partition function, we introduce a further assumption:

A.4. All players are ex-ante identical, which means that each player has the same strategy space in the second stage emission game.

This assumption allows us to adopt an equal sharing payoff division rule inside any coalition, i.e. each player in a given coalition receives the same payoff as the other members[4]. Furthermore the symmetry assumption implies that a coalition C_i can be identified with its size c_i and a coalition structure can be denoted by $\pi=\{c_1,c_2, ... ,c_m\}$, where $\sum_i c_i = n$. As a consequence, the payoff received by the players only depends on coalition sizes and not on the identities of the coalition members. The per-member partition function (partition function hereon) can thus be denoted by $p(k;\ \pi)$, which represents the payoff of a player belonging to the size-k coalition in the coalition structure π. Finally, let us denote by $\pi = \{a_{(r)}, ...\}$ r size-a coalitions in the coalition structure π.

Recent developments of the theory of endogenous coalition formation (Cf. Bloch, 1997) have stressed the implications of allowing players to join different coalitions. However, in the case of global warming and climate change, the negotiating agenda focuses on a single agreement that countries have to decide whether or not to sign. Therefore, we assume that:

A.5. Countries are proposed to sign a single agreement. Hence, those which do not sign cannot propose a different agreement. From a game-theoretic viewpoint, this implies that only one coalition can be formed, the remaining defecting players playing as singletons. This assumption will be relaxed in Section 5.

Finally, we need to introduce a technical assumptions which is necessary to reduce the number of equilibria of the coalition formation game:

A.6. Above a minimum coalition size[5], each country's payoff function increases monotonically with respect to the coalition size (the number of signatories in the symmetric case).[6]

This last assumption is quite natural in the case of negotiations on climate change control. Indeed, being climate a public good, each country which finds it convenient to reduce its own GHG

[4] We consider the equal sharing rule as an assumption since it is not endogenously determined in the model. However Ray and Vohra (1996) provides a vindication for this assumption.

[5] The minimum size is equal to 2 in the case of orthogonal free-riding. In this case, the individual payoff function increases for all feasible values of the coalition size. This may not be the case with non-orthogonal free-riding.

[6] This assumption excludes the possibility of "exclusive membership equilibria" where the group of cooperating countries can refuse entry to a country which wants to join the coalition (Yi, 1997).

emissions, provides a positive contribution to the welfare of all countries (both inside and outside the coalition).

3. The coalition game

The first stage game consists of a binary choice game (joining the coalition or behaving as a lone free-rider) and the outcome of this interaction is a single coalition structure $\pi = \{c, 1_{(n-c)}\}$. The distinctive features of the game describing negotiations on climate change control are as follows**:**

Positive spillovers. In any single coalition structure if some players form a coalition, other players are better off. Then the partition function of any player outside the coalition (*non member function*) is increasing in c for all the value of c. Formally:

$p(1; \pi)$, where $\pi = \{c, 1_{(n-c)}\}$, is an increasing function of c.

The existence of positive spillovers creates an incentive to free-ride on the coalition action. In particular, there may emerge two different free-riding behaviour patterns according to the slope of players' reaction functions (Carraro and Siniscalco, 1993).

- Orthogonal free-riding. When players' reaction functions in the emission game are orthogonal, free riders just benefit from the cooperative action of the coalition and they cannot damage it (there is no "carbon leakage").

- Non orthogonal free-riding. When players' reaction functions in the emission game are not orthogonal, i.e. in an environment in which there is a great interdependence between countries' emission strategies, free-riders can damage the coalition by increasing their own emissions whenever cooperating countries reduce their own. In this case, free-riding can lead to decreasing returns of cooperation (in particular for small coalitions). In words, this implies that a small number of cooperators may loose from cooperation because of the increased emissions in the free-riding countries. Let us denote by $c^\wedge$ the size a coalition has to reach in order to start benefiting from cooperation and to obtain an increasing benefit as the coalition becomes larger and larger ($c^\wedge$ is the minimum size of assumption A.6).

In the case of climate change both situations are possible. Current estimates of "carbon leakage" ranges from very small values (Cf. OECD,1993) to quite large ones (Ulph, 1993). Therefore it is worth analysing both cases and the impact of different degrees of "carbon leakage" on the outcome of negotiations on climate change control.

Given these features of the n-country game, let us characterise its equilibrium. As said, countries decide independently, simultaneously, and non-cooperatively whether or not to sign the agreement on climate control. Hence, the concept of Nash equilibrium (NE) is the most appropriate for the first stage of the game – the coalition game. The Nash equilibrium is completely characterised by the following two properties, first derived in the cartel literature (D'Aspremont et al., 1983) and then often used also in the environmental literature (Carraro and Siniscalco, 1993, Barrett, 1994).

Profitability. A coalition is profitable if each cooperating player gets a payoff larger than the one he would obtain in the autarchic state, i.e. when no coalition forms. Formally:

(1) $$p(c; \pi) > p(1; \pi^S),$$

where $\pi = \{c, 1_{(n-c)}\}$ and $\pi^S = \{1_n\}$, for all $i \in c$.

From eq. (1), the value of the minimal profitable coalition size can be derived. Denote it by c^m. This value depends on the strategic interaction between the coalition and the singleton players. In particular, with orthogonal free-riding any coalition size is profitable and c^m is simply two (Carraro and Siniscalco, 1992). By contrast, with non-orthogonal free-riding behaviour the coalition has to reach a minimal size by which it can offset the damaging free-riders' action. This size is generally larger than two. Note that c^ and c^m do not necessarily coincide (see Fig. 3).

- Stability. A coalition is stable if it is both internally and externally stable. It is internally stable if no cooperating player is better off by defecting in order to form a singleton[7]. Formally:

(2a) $$p(c;\, \pi) \geq p(1;\, \pi'),$$

where $\pi=\{c,1_{(n-c)}\}$ and $\pi' = \pi \backslash \{c\} \cup \{c\text{-}1,\, 1\}$for all $i \in c$.[8] It is externally stable if no singleton is better off by joining the coalition c. Formally:

(2b) $$p(1;\, \pi) > p(c';\, \pi'),$$

where $\pi=\{c,1_{(n-c)}\}$ and $\pi' = \pi \backslash \{c,1\} \cup \{c'\}$ and $c' = c+1$ for all $i \notin c$.

Notice that each country chooses his strategy taking the action of the other countries as given. Then, each player, in order to define his (individually) optimal strategy, compares for each conceivable c his payoff when he stays out the coalition with his payoff when he stays in the coalition.

A useful tool to analyse the stability of the coalition, i.e. the Nash equilibrium of the coalition game, is the stability function $L(c)$ proposed in Carraro and Siniscalco (1992). This function describes a country's incentive to join a coalition c:

(3) $$L(c) = p(c;\pi) - p(1;\pi'),$$

where $\pi=\{c,1_{n-c}\}$ and $\pi' = \{c',1_{n-c'}\}$ where $c'=c\text{-}1$

In order to understand the behaviour of the stability function, we need to describe the non-member function $p(1;\pi')$ and the member one $p(c;\pi)$. By the positive spillover property, the free-rider payoff function increases with the size of c, as shown in Fig.1. The member function $p(c;\pi)$ is drawn in Fig. 2 for the case in which free-riding is orthogonal, whereas the same function with non-orthogonal free-riding is represented in Fig.3.

Moreover, positive spillovers imply that the stability function becomes negative at least when $c = n$. Indeed, when n-1 countries reduce their emissions, the n-th one can enjoy a clean environment without paying any cost. Hence the problem arises from the fact that the grand coalition is the efficient outcome (because of assumption A.6) but it is not stable. The size of the stable coalition is determined by conditions (2), i.e. by the largest integer c^* smaller than c', where c' is defined by $L(c') = 0$ and $L'(c) < 0$ (again assumption A.6 guarantees the uniqueness of c')[9]. This size is the minimal externally stable and the maximal internally stable. The stability function is a decreasing function of c as in Fig. 4. Note that c^* is not necessarily greater than one.

Given the above assumptions and equilibrium concept, we can prove the following:

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7 Yi (1997) denotes this condition by the term "stand alone stable".

8 We suppose that if a player is indifferent between joining the coalition or defecting, then he joins the coalition.

9 This assumption can easily be relaxed.

Proposition 1. The NE of a simultaneous single coalition game is the following coalition structure:

- when $c^m > c^*$, $\{1_n\}$, i.e. the singleton structure (π^S hereon)
- when $c^m \leq c^*$, $\{c^*, 1_{(n-c^*)}\}$ (π^* hereon)

Proof: When $c^m \leq c^*$ the profitability condition is satisfied. Then by definition of c^*, a single coalition structure in which $c<c^*$ is not a NE, because a singleton's best replay is to join the coalition. On the other hand, in a single coalition structure in which $c>c^*$ the best replay of a cooperating player is to defect. Thereby only when $c = c^*$ no country wants to change his strategy. The equilibrium coalition structure is thus $\{c^*, 1_{(n-c^*)}\}$.

When $c^m > c^*$, a coalition structure in which $c>c^m>c^*$ is not stable, because a cooperating player's best replay is to defect. Besides, in all single coalition structure in which $c<c^{m,}$ by definition of c^m all cooperating players have an incentive to leave the coalition since they gain a larger payoff in the non cooperative state. Then the only NE structure of the game is the non cooperative outcome, i.e. the coalition structure π^S with n singletons. □

To understand the relevance of this result, consider Table 1, which shows the payoff that can be obtained by defectors and cooperators under different coalition structures and assuming orthogonal free-riding. In each row, the payoff of singletons is shown first. The value in Table 1 are computed using the simple model proposed in Carraro and Siniscalco (1992) and then used by Barrett (1994), Chander and Tulkens (1995).

Table 1. **A single coalition game with orthogonal free-riding (no leakage)**

Coalition structure	Per-member partition function					
1,1,1,1,1,1,	0	0	0	0	0	0
1,1,1,1,2	2	2	2	2	0,5	0,5
1,1,1,3	6	6	6	2	2	2
1,1,4	12	12	4,5	4,5	4,5	4,5
1,5	20	8	8	8	8	8
6	12,5	12,5	12,5	12,5	12,5	12,5

Let us first consider the structure of incentives that characterises this game. It can be summarised by the following three facts:

- *Fact 1*: the profitability condition is satisfied for all c.
- *Fact 2*: the coalition is internally stable for all $c \leq 3$.
- *Fact 3*: the coalition is externally stable for all $c \geq 3$.

As a consequence, the NE of this game is $\pi^* = \{3,1,1,1\}$. Consider indeed any coalition structure in which the coalition is larger than three. By Fact 2, the best replay of one of the coalition members is to defect from the coalition. On the other hand, consider any coalition structure in which the coalition is smaller than three. Then, by Fact 3 the best replay of one of the players outside the coalition is joining the coalition. Fact 1 guarantees that the stable coalition is also profitable.

Consider now the case in which there is carbon leakage, i.e. free-riding is non-orthogonal. The values of countries' payoff are summarised in Table 2.

Table 2. **A single coalition game with non-orthogonal free-riding (leakage)**

Coalition structure	Per-member partition function					
1,1,1,1,1,1	1/49	1/49	1/49	1/49	1/49	1/49
1,1,1,1,2	1/36	1/36	1/36	1/36	1/72	1/72
1,1,1,3	1/25	1/25	1/25	1/75	1/75	1/75
1,1,4	1/16	1/16	1/64	1/64	1/64	1/64
1,5	1/9	1/45	1/45	1/45	1/45	1/45
6	1/24	½4	1/24	1/24	1/24	1/24

Again the incentive system is summarised by the following three facts:

- *Fact 1*: the profitability condition is satisfied for all c≥5
- *Fact 2*: the coalition is internally stable for all c<1
- *Fact 3*: the coalition is externally stable for all c≥1

As a consequence, the NE of this game is π* = {1,1,1,1,1,1}. Consider indeed any coalition structure in which the coalition is larger than one. By Fact 2, the best replay of any coalition member is to defect until the singleton structure is reached. Furthermore, by Fact 3 no singleton would be better off by joining the coalition in any coalition structure.

One may argue that the above conclusions are largely theoretical and crucially depend on the assumption of symmetric countries. We would like to show that this is only partly true by considering a simple empirical model which reproduces countries' incentives (costs and benefits) to join an international agreement on climate control (see Botteon and Carraro, 1997a,b for a detailed description of the model). Simulations of the model enable us to determine the Nash equilibrium of the coalition game and to identify the countries which are going to sign the agreement. Let us consider the case in which there is leakage and in which LDCs place a low economic value to environmental benefits arising from GHGs emission reductions (this case was not analysed in Botteon and Carraro, 1997a,b,c). In the model, the world is divided into six regions, Japan, North America, EU, Eastern Countries and Russia, China and India, Other Countries. It is assumed that negotiations take place only among the first five groups of countries, the other ones always prefer to free-ride.

Table 3 shows the equilibrium outcome without leakage (first row), where, as expected from the above theoretical results, only three groups of countries are going to sign the agreement. Notice that the equilibrium coalition is computed under two different burden-sharing rules, Nash bargaining and

Shapley value, because in the case of asymmetric countries game theory proposes several solutions to determine how cooperating countries share the abatement burden.

As leakage increases, no coalition forms, until leakage becomes very large, thus leading to the formation of larger and larger coalitions. How can this empirical result, which was not found in the previous theoretical analysis, can be explained?

The explanation is provided in Carraro and Botteon (1997c) where two effects of leakage are highlighted. On the one hand, carbon leakage tends to reduce the size of stable coalitions and even the likelihood of observing a stable coalition at the equilibrium because it reduces the coalition benefit and increases the incentive to free ride when the coalition is small. On the other hand, carbon leakage increases the return from large coalitions, and decreases the return from free-riding when the coalition is large. Therefore, carbon leakage, if sufficiently large, can induce the formation of large environmental coalitions. Hence, there may be two equilibrium coalition structures: one formed by a small coalition (or by the non-cooperative equilibrium) and one formed by the grand coalition (or a very large one).[10] How to move from one equilibrium to the other is a matter of coordination, which demands for new international institutions.

Table 3. **Stable coalitions and leakage. Low perceived damage in LDCs**

Leakage in Country					**Stable coalitions**	
JAP	**NA**	**EU**	**EE+R**	**C+I**	**Nash Bargaining**	**Shapley-value**
0	0	0	0	0	{JAP,NA,EU} {JAP,EU,EE+R} {JAP,NA,EE+R}	{NA,EU,EE+R}
1%	7%	7%	15%	15%	No Equilibrium Coalition	No Equilibrium Coalition
1%	7%	7%	15%	30%	No Equilibrium Coalition	No Equilibrium Coalition
1%	7%	7%	30%	30%	No Equilibrium Coalition	No Equilibrium Coalition
3%	7%	7%	15%	30%	{NA,EU} {NA,EU,EE+R}	{NA,EU,EE+R}
3%	7%	7%	30%	30%	{NA,EU}	{NA,EU,EE+R}
5%	7%	7%	15%	15%	{JAP,NA, EU,EE+R}	{JAP,NA,EU, EE+R}
5%	7%	15%	15%	15%	{JAP,NA, EU,EE+R,C+I}	{JAP,NA, EU,EE+R,C+I}

4. Enlarging the Kyoto protocol. Transfers, Linkage, Threats.

What are the implications of the above results? First, the game structure which captures countries' interactions is not a prisoners' dilemma, but rather a chicken game, in which at least two groups of players (and two roles: signatories and defectors) co-exist. More precisely, a profitable and stable coalition may emerge (if free-riding is orthogonal or near-orthogonal) out of the two stage-game previously described.

This has an important implication. If an equilibrium coalition exists, the outcome of the game is not the one in which no cooperation takes place (no countries sign the agreement) as it could be expected given the public good nature of the global environment. At the equilibrium there are instead two groups of countries, signatories and defectors, where the size of the group of signatories crucially depends on the slope of countries' reaction functions (the size of carbon leakage).

[10] These results are also shown from a theoretical view point in Carraro and Moriconi (1998).

Moreover, this first conclusion is consistent with the present negotiating agenda whose main goal is to achieve, at least as a first step, the ratification of the Kyoto protocol which is signed only by Annex 1 (or Annex B in the protocol) countries.

Second, the stable (and Pareto optimal because the payoff function increases monotonically) coalition is generally formed by a low number of players.[11] In the example above, at most 3 players, whatever *n*, join the stable coalition and only in the favourable case of orthogonal free-riding.

As a consequence of this last result, the recent literature on international environmental agreements (see Carraro, 1997a,b for a survey) focused on ways of broadening the "endogenous" stable coalition by "exogenously" introducing appropriate additional policy measures. Three ideas deserve our attention.

- Transfers

Transfers are often proposed to tackle the profitability dimension of international negotiations, i.e. to compensate those countries which, because of their asymmetries, would lose from signing the agreement. Transfers may also be an important tool to expand an originally stable, but small, environmental coalition. However, as shown in Carraro and Siniscalco (1993), countries which accept to implement a transfer program to non-signatories must be committed to cooperation (this condition is weaker with asymmetric countries; see Botteon and Carraro, 1997a). As a consequence the international agreement becomes partially self-enforcing.

The model used above to compute the equilibrium coalition structure in the presence of leakage can also be used to analyse the equilibrium coalition structures in the presence of self-financed transfers. Some results are shown in Table 4.

Table 4. Stable coalitions with transfers. Low perceived damage in LDCs

Starting stable coalition	**Stabilised coalition without commitment**	**Stabilised coalition with commitment**	**Total net gains to expand the coalition**
Nash-Bargaining			
{JAP,NA,EU}	{JAP,NA,EU}	{JAP,NA,EU, EE+R} {JAP,NA,EU,C+I} {JAP,NA,EU, EE+R,C+I}	1089 2217 3516
Shapley value			
{JAP,NA,EU}	{JAP,NA,EU, EE+R} {JAP,NA,EU, C+I} {JAP,NA,EU,EE+R,C+I}	{JAP,NA,EU, EE+R} {JAP,NA,EU, C+I} {JAP,NA,EU, EE+R,C+I}	988 3412 3890

Notice that, using the Nash bargaining solution, transfers cannot be used to add additional countries to the initially stable coalition in the absence of a form of partial commitment. By contrast, if the countries in the initially stable coalition are committed to cooperation, then a system of transfers can induce free-riders to sign, thus leading to the grand coalition. The results are different using the Shapley value burden-sharing rule, because in this case the grand coalition can be achieved even without commitment (see Botteon and Carraro, 1997a for a more detailed discussion of this case).

[11] This conclusion depends on the assumption on the returns from abatement activities and on the presence of abatement fixed costs (Barrett, 1994; Heal, 1994).

- Issue linkage

As for transfers, the linkage of environmental negotiations to other economic issues (e.g. trade or technological cooperation) may be useful: (a) to reduce the constraints that asymmetries impose on the emergence of stable environmental agreements;[12] (b) to increase the size of the stable coalition. This second objective can be achieved even when all countries gain from signing the agreement if issue linkage is designed to offset countries' free-riding incentives (Cf. Carraro and Siniscalco, 1995). This is the case when the negotiation on an issue with excludable benefits (a club good) is linked to the environmental negotiation (which, if successful, typically provides a public good, i.e. a non-excludable benefit). An example could be the linkage of environmental negotiations with negotiations on technological cooperation whose benefits are largely shared among the signatories whenever innovation spillovers to non-signatories are low (Cf. Carraro and Siniscalco, 1997).

Can issue linkage lead negotiating countries to form the grand coalition? The answer may be positive in the case of symmetric countries (it depends on the relative benefits derived from getting the club good with respect to the benefits provided by the public good). However, two additional problems arise. First, the stable coalition may not be optimal; second, there may be a conflict among countries about which coalition to form. The optimal coalition for country i is defined as the coalition which maximises country i's payoff. It is therefore generally different from the stable one. In particular, in the case in which R&D and environmental cooperation are linked, the optimal coalition is smaller than the stable coalition (Carraro and Siniscalco, 1997). Moreover, there may be no consensus among the countries on which coalition is actually optimal. For example, country i may prefer some countries, say j and h, as partners in the cooperating group, but these countries may want to sign the agreement with country k, rather than with i. And k may prefer i and h rather than j and k. In this case, a voting game must be analysed. This game may not possess an equilibrium, i.e. no stable agreement would be signed even when at least one stable coalition exists.

Let us further explain these two conclusions through an example by starting from the first one. Why is the optimal coalition smaller than the stable one? In the game in which environmental negotiations are linked to cooperation on R&D, the environmental benefit increases with the number of countries in the coalition (more abatement is carried out). Hence the largest environmental benefit is achieved when all countries sign the agreement. This is not the case for R&D cooperation. Countries which join the R&D coalition share two benefits. First they have at their disposal a more efficient technology (production costs are lowered by R&D cooperation). Second, they share a competitive advantage vis a vis those countries which do not belong to the R&D cooperation. This implies that countries in the coalition have larger market share and profits. This second benefit is lost as soon as all countries enter the R&D coalition. Therefore, there is an incentive for some countries to exclude other ones from the coalition. When "issue linkage" takes place, the incentive to exclude some countries may still arise if the relative weight of benefits from R&D cooperation is sufficiently large.

The second problem arises only when countries are asymmetric and is strictly linked to the first one. If countries in the coalition have an incentive to exclude some other countries, they may disagree on the countries to be excluded. This type of conflict may even undermine the emergence of the initial coalition, as shown in Botteon and Carraro (1997b).

This implies that one must be cautious when proposing "issue linkage" as the way of solving the problems often arising in international environmental negotiations. Even when the usual profitability and stability problems could be solved, the conflict between optimality and stability of coalitions may be such that "issue linkage" reduces, rather than increases, the number of signatories of the international environmental agreement. In some cases, there may even exist no equilibrium coalition.

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12 This point was made by Folmer et al (1993) and Cesar and De Zeeuw (1996).

- Threats

The number of signatories of an international environmental agreement could be increased were non signatories threatened to be punished through adequate economic (e.g. trade) sanctions (Cf. Barrett, 1995, 1997b). However, credible threats are difficult to design. Emissions themselves are hardly a credible threat, because countries are unlikely to sustain self-damaging policies (e.g. when the "social clauses" of GATT are violated). Moreover, in this case, asymmetries play a double role. On the one hand, some countries may not gain from signing the environmental agreement; on the other hand, some countries, even when gaining from environmental cooperation, may lose from carrying out the economic sanctions. This may reduce the effectiveness of threats in increasing the number of signatories of international environmental agreements.

5. Environmental regional agreements

The results proposed in previous sections crucially depend on Assumption 5 that imposes that countries can negotiate on a single agreement. If instead countries can choose whether to sign a single global agreement or a region-specific agreement, results may drastically change.

This change of assumptions has important implications. Whereas in the previous sections only one coalition could emerge, the free-riding countries behaving as singletons, in this section we allow for the emergence of a complex coalition structure in which several coalitions may emerge at the equilibrium. The problem is to determine which equilibrium structure is most likely. Whether one in which one coalition is formed, or one in which $k>1$ coalitions, which interact among each others, characterise the equilibrium of the non-cooperative coalition game.

The implications for environmental negotiations are clear. In the latter case, there would not be one environmental agreement, but k agreements signed by k groups of countries. The multiplicity of coalitions may allow for region-specific agreements in which the characteristics of countries in the region are better reflected by the contents of the agreement.

Notice that several definitions have to be modified to take into account that coalitions and countries are now the actors of the game. For example, in a single coalition game free-riders can behave solely as singletons and thereby the worth of the (unique) coalition is easily determined and the stability of a coalition structure coincides with the stability of such a coalition. By contrast, in a multi-coalitional game, the complement set behaviour is not fixed and the worth of a coalition is not univocally defined. In particular the worth of a coalition depends on the behaviour of the complement set and this is why considering the stability of a single coalition is meaningless in a multi-coalition game. Unfortunately the feasible coalition structures increase significantly as the number of players increases.

The concept of spillovers and the related definition of free-rider also have to be modified. We say that there are coalitional environmental spillovers (from one coalition to the others and to free-riders) if, when coalitions merge to form a larger coalition, the other coalitions and the singletons not affected by the change are better off. In words, the payoff of a player is larger the larger the size and the lower the number of the coalitions formed by the resulting complementary set. This implies that the complementary set defined by a singleton structure embodies the worst possible complement structure for a coalition, i.e. the minimax one[13]. In this sense the single coalition game is referred to as a benchmark for the multi-coalition game, since it represents the minimum payoff any coalition can obtain in a multi-coalition game.

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[13] Furthermore in a game with positive spillovers the minimax and the maximin strategies coincide.

The free-riding incentive, which naturally arises in a game with positive externalities, can be described as follows in a multi-coalition game. In any coalition structure, members of small coalitions have higher payoffs than members of big coalitions. The limit case is the one of singletons (i.e. coalitions formed by one player only) which receive the greatest net benefit from the other coalitions' abatement.[14]

Even if non singleton coalitions can form, the stability and the profitability condition are defined with respect to an individual viewpoint in keeping with the spirit of a non cooperative approach. Therefore, a coalition structure π is profitable if any coalition s in π is profitable. A coalition $c \in \pi$ is profitable if each cooperating player belonging to c gets a payoff larger than the one he would get in the singleton structure.

Let us now consider the stability condition. Consider a coalition belonging to any coalition structure: since it is always possible for any cooperating country to deviate to form a singleton, the internal stability condition is again a necessary condition. In the single coalition case, this condition was coupled with the external stability one. Indeed in the single coalition case, these two conditions are sufficient to define the equilibrium coalition structure, since countries have only two possible strategic choices: joining a coalition (i.e. signing the agreement) or behaving as a lone free-rider (singleton). By contrast, in the multi-coalition game, the first stage is no more a binary choice game, since if a country chooses to cooperate, it has also to choose which coalition to join. This is why a further condition on the entire coalition structure has to be added: the intracoalition stability.

Moreover, since in the multi-coalition game the complementary set of a coalition does not necessarily behave as a singleton set, in the stability condition we need to account for the behaviour of the complementary set. Here we use a sort of Nash assumption. Players in a given coalition s assume that the coalition structure formed by players not in s remains constant. We can therefore say that a coalition structure π is stable if each coalition $s \in \pi$ is:

- internally stable, i.e. no cooperating player would be better off by leaving the coalition to form a singleton;

- external stable, i.e. no singleton $i \in \pi$ would be better off by joining any coalition $s \in \pi$.

- intracoalition stable, i.e. no player belonging to s would be better off by leaving s to join any coalition $s' \in \pi$.

Unfortunately, game theory is far from having achieved a well-defined non-cooperative theory of coalition formation under the above general assumptions and definitions. There are several stability concepts that can be used and which unfortunately provide different equilibrium coalition structures. Among them, let us recall the concept of equilibrium binding agreements proposed by Ray and Vohra (1996), the concepts of α-stability and β-stability proposed in Hart and Kurz (1983), the sequential stability concept of Bloch (1994), the open-membership stability proposed by Yi and Shin (1994) and the farsighted stability concept used in Chew (1994), Mariotti (1997).

Despite the large number of equilibrium concepts, the results that can be derived from applying these theoretical refinements to a simple model of climate change negotiations are quite interesting and share some common features:

- the equilibrium coalition structure is not formed by a single coalition. In general, many coalitions form at the equilibrium;

[14] Yi (1997) shows that the partition function of a multicoalition game with positive externalities usually satisfies these two properties.

- the grand coalition, in which all countries sign the same environmental agreement, is unlikely to be an equilibrium;

- coalitions of different sizes may emerge at the equilibrium (even when countries are symmetric).

The specific results on the size of the coalitions depend on the model structure and in particular on the slope of countries' reaction functions, i.e. on the presence of carbon leakage. If there is no leakage and countries are symmetric, and if Assumption A1 is satisfied, then the Nash equilibrium of the multi-coalition game is characterised by many small coalitions, each one satisfying the properties of internal and external stability (this result is shown in Carraro and Moriconi, 1998).

In order to understand this result, let us consider the same example that was used in Section 2 to illustrate the equilibrium of a single coalition game. In Table 5, we show all coalition structures that can emerge when multiple coalitions are allowed for and the payoff that countries can achieve.

Table 5. A multiple coalition game with orthogonal free-riding

Coalition structures	Per-member partition function					
1,1,1,1,1,1	0	0	0	0	0	0
1,1,1,1,2	2	2	2	2	0,5	0,5
1,1,1,3	6	6	6	2	2	2
1,1,4	12	12	4,5	4,5	4,5	4,5
1,5	20	8	8	8	8	8
6	12,5	12,5	12,5	12,5	12,5	12,5
1,2,3	8	6,5	6,5	4	4	4
2,2,2	4,5	4,5	4,5	4,5	4,5	4,5
3,3	8	8	8	8	8	8
2,4	12,5	12,5	6,5	6,5	6,5	6,5
1,1,2,2	4	4	2,5	2,5	2,5	2,5

The incentives to coalition formation are summarised by the following five facts:

Fact 1: the profitability condition is satisfied for all c in any coalition structure (i.e. c^m=2).
Fact 2: if c>3, a country's payoff is not lower when it belongs to the coalition than when it defects and the coalition becomes smaller (i.e. c*=3).
Fact 3: if c>3, a country's payoff is larger when it does not belong to the coalition than when it joins it.
Fact 4: if the difference between the sizes of the smallest and the largest coalition is more than one, a player belonging to the largest coalition is better off by defecting and joining the smallest coalition.

Fact 5: if two coalitions d and c, belonging to the same coalition structure, are such that $d \geq c/2$, members of both c and d would be better off by merging.

Using these facts it is easy to conclude that there are two stable coalition structures: {2,2,2} and {3,3}. By introducing a further refinement, i.e. by using the Coalition Proof Nash equilibrium rather than the Nash equilibrium of the multi-coalition game, the conclusion is that the only coalition structure is {3,3} (see Carraro and Moriconi, 1998).

Let us recall that, in the case of a single agreement, the equilibrium coalition structure was shown to be {1,1,1,3}. Which one of the two coalition structures is welfare maximising? In the simple example represented in Table 5, {3,3} Pareto dominates {1,1,1,3} because both cooperators and free-riders are better off. Hence the conclusion is that, at the equilibrium, two regional agreements formed by three countries each provide all countries with a higher net benefit than a single agreement, which is signed by only three countries at the equilibrium.

Is this conclusion general enough to provide sound support for policy recommendations? The answer is no, because there may be examples in which a single agreement is preferred, at least from an environmental viewpoint, to many small regional agreements. Moreover, the conclusion crucially depends on the choice of the equilibrium concept and on the absence of leakage. However, it provides important insights on the feasible outcomes of environmental negotiation processes. The problem still to be solved can be phrased as follows. If countries are free to choose the number and features of agreements, then the negotiation process is likely to lead to several agreements. As a consequence, if the negotiating agenda focuses on a single agreement, will it reduce the probability of stabilising climate change? Should countries and international institutions realise that climate change control can be easier to achieve if many regional agreements, which account for the specific characteristics of countries in the region, are proposed?

Notice that these questions and doubts implicitly contain an extension of previous theoretical results, derived for the case of symmetric countries, to the case of asymmetric countries. Unfortunately, there is no theoretical analysis that can support this type of extension, which can therefore be accepted only as very preliminary. However, results contained in Barrett (1997a), Botteon-Carraro (1997a) for the case in which a single coalition is assumed at the equilibrium, suggest that theoretical results derived for the case of symmetric countries are largely confirmed when countries' asymmetries are introduced into the model. More work on this issue would nonetheless be very important.

The consequence of the results proposed in this section, albeit preliminary and restricted to the case of symmetric countries, is that the structure of international environmental agreements is a crucial dimension of the negotiating process. If all countries negotiate on a single agreement the incentives to sign are lower than those which characterise a multiple agreement negotiating process. At the equilibrium, the environmental benefit (quality) would also be lower. Should a change of strategy be proposed at the institutional level or will it emerge endogenously?

6. Conclusions and Further Research Directions

Even if the literature on international environmental negotiations and cooperation is likely to develop further in the next years and to provide new results on the existence and features of self-enforcing agreements, there are a few conclusions that can be drawn. First, the attempt to achieve an agreement signed by all countries is likely to be unsuccessful if the negotiation is restricted to emissions only. Second, even when the negotiations is broadened to include transfers and/or it is linked to negotiations on other international issues, the outcome may not be the grand coalition, because of lack of commitment (in the case of transfers) or because of the conflict between optimality and stability of the coalition (in the case of issue linkage). Third, when more than one coalition is allowed for, the equilibrium coalition structure which endogenously emerges from the negotiation process is characterised by several coalitions. This implies that regional agreements on climate change may be a likely outcome of the negotiation process.

There are several directions of further research that deserve additional efforts. The strategic dimension of environmental negotiations, both at the international and domestic levels (voters may be asked to ratify an environmental agreement) opens interesting political economy problems (Currarini and Tulkens, 1997; Carraro and Siniscalco, 1998). The lack of a supra-national authority calls for an analysis of new international institutions (Compte and Jehiel, 1997 propose an international arbitrator). The possibility to expand coalitions by linking environmental and trade negotiations requires further theoretical and empirical analyses. A dynamic framework may be more appropriate to deal with environmental issues in which the stock of pollutants, rather than the flow (emissions) is the crucial variable to monitor (see Maler, 1990; Van der Ploeg-De Zeeuw, 1992). Finally, the analysis of the impact of transfers and issue linkage on the size of stable coalitions should be extended to the theoretical approach described in Section 5, where multiple coalitions are allowed for.

More empirical work is also necessary. The existing empirical literature is large, but it assumes the exogenous formation of environmental coalitions, and assesses the effects of countries' decisions to sign the agreement on the main economic and environmental variables. However, an empirical analysis of the incentives to sign the agreement and of the negotiation process that leads to the endogenous formation of the coalition is still missing. Moreover, the empirical analysis would help understanding whether the theoretical results, usually derived in the case of symmetric countries, still hold when the negotiations take place between countries of different sizes, natural resource endowments, development stages, etc.

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FIGURE 1. **Non member partition function**

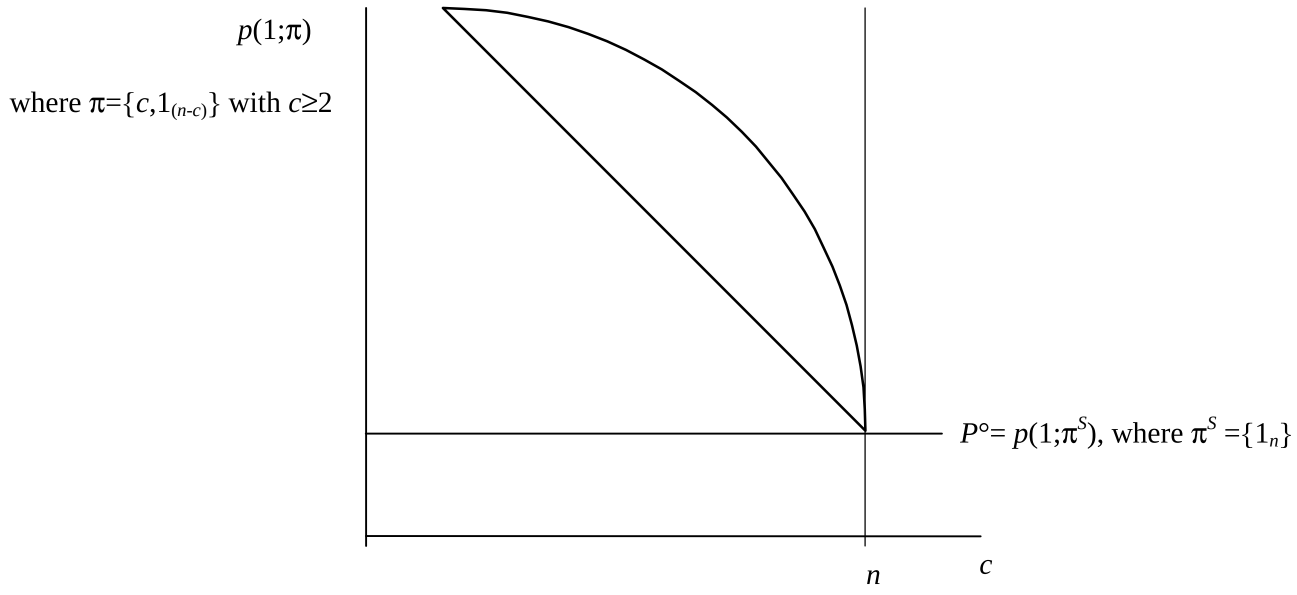

FIGURE 2. **Member partition function with orthogonal free-riding**

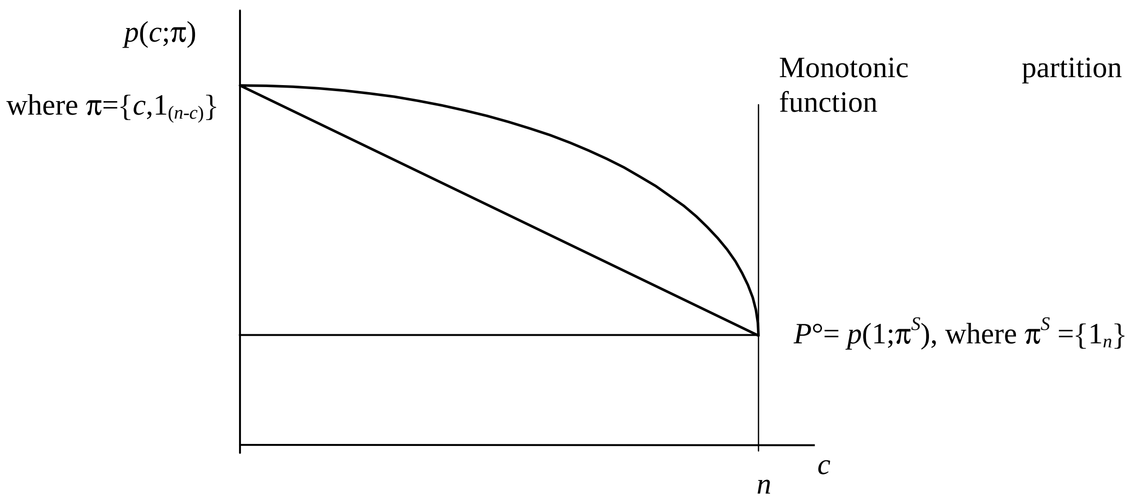

FIGURE 3. **Member partition function with non-orthogonal free-riding**

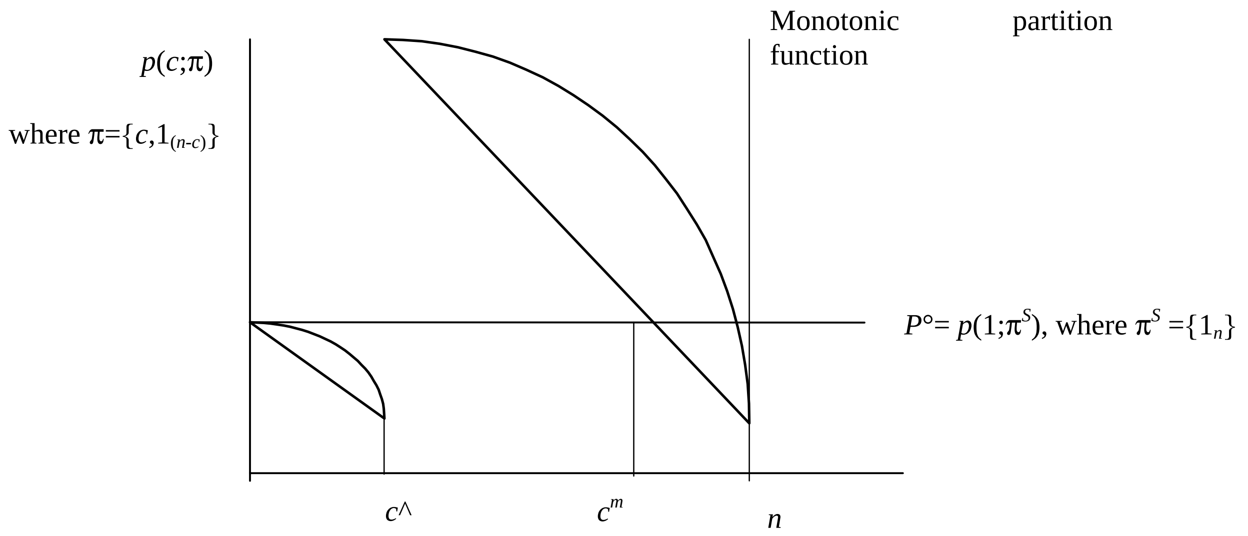

FIGURE 4. **Stability function**