A Game-theoretic Analysis on Negotiation Mechanisms for Climate Change Mitigation

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Abstract

We examined climate change negotiation in a game-theoretic framework. We formulated the international climate change negotiation as a coalition formation game and applied the equilibrium concept of 'stable coalition', under which no member has an incentive to leave the coalition (internally stable) and no non-member has an incentive to join the coalition (externally stable). The behavior of self-interested countries or groups of countries was analyzed with the application of global climate change simulation model, STACO, developed by Finus, Ierland and Dellink (2003).

The results of this study reaffirm the conclusion of most of previous research: Stable coalitions to address climate change are likely to be limited to a relatively small number of large regions representing at least 30% of global emissions. Our simulation results show there is no stable coalition structure without welfare transfers. Even with welfare transfers the stable coalitions are relatively small and typically include a mix of regions with low marginal emissions abatement costs and low marginal climate change damages and regions with high marginal emissions abatements costs and high marginal climate change damages. This phenomenon stems from the free-rider incentives inherent in public good problem. The free-rider incentive becomes stronger as the size of coalition increases. The burden-sharing rule can have a significant impact on the size and composition of the stable coalitions and hence on the share of the maximum potential gains from cooperation achieved.

Imperfect cooperation can lead to a larger stable coalition that achieves a larger share of the maximum potential gains from cooperation. A committed coalition can increase its membership and efficiency significantly by sharing the gains from increased cooperation with new members.

One of the most important observations of the paper is that some forms of commitments by some countries can expand the coalitions significantly and it is possible to achieve most of potential benefits. The policy implication is that strong commitments by major countries can

play a vital role in establishing an effective global climate change mitigation regime.

China is found to be an essential member of virtually every stable coalition. China can contribute more to the welfare gains from forming a coalition than any other region. An equitable transfer mechanism needs to be devised and applied in future negotiations to induce participation by China.

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Chapter 1. Introduction

1. Background and motivation

Climate change is one of the broadest and most complex issues of international environmental cooperation. International negotiations on climate change mitigation policy span more than a decade. As a consequence, there are many achievements and many challenges that remain to be addressed.

Of the many achievements of international climate change policy, three appear to be particularly significant. First, the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol have created a solid institutional basis for the negotiating process, including principles, setting an objective, and instituting decision-making procedures that allow the international climate change regime to evolve. This framework has enabled Parties to overcome a number of major difficulties. Second, the Kyoto Protocol incorporates quantified emission targets for industrialized countries that appear, despite a number of shortcomings, to be an important element of the way forward.[1] Third, the establishment of three trading mechanisms for meeting mitigation obligations should reduce the cost of meeting the regime's emissions limitation commitments and thus strengthen the forces that drive climate protection.[2] (Oberthur and Ott (2004))

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[1] Under both the Convention and the Kyoto Protocol, only industrialized countries (Annex I Parties) are subject to emission caps. The Convention requires Annex I Parties to take policies and measures with the aim of returning their emissions of carbon dioxide and other greenhouse gases to their 1990 levels by 2000. Most of the Annex I Parties did not achieve this target. The Kyoto Protocol strengthens the Convention by setting individual, legally binding caps on the emissions of Annex I Parties. Each Annex I Party must reduce its emissions or, in some cases, limit its emissions growth from 1990 levels for the 2008-2012 commitment period.

[2] The Kyoto Protocol establishes three emissions trading mechanisms: emissions trading between industrialized countries (Article 17), Joint Implementation of projects by two industrialized countries to achieve additional emission reductions (Article 6), and joint implementation of projects by developing and industrialized countries in the framework of the Clean Development Mechanism (Article 12). All three mechanisms allow industrialized countries with high abatement costs to acquire cheaper emission credits abroad. As a result, the overall costs of meeting the emissions limitation commitments of Annex I Parties to the Protocol are reduced.

With Russian ratification of the Kyoto Protocol on November 18, 2004, it will enter into force on February 16, 2005, with the participation of more than 130 countries including about 35 Annex I countries.[3]

In spite of these achievements, the international climate change regime faces significant challenges. One of the most serious problems is the lack of stability of international agreements. The Kyoto Protocol, agreed at the third Conference of the Parties to UNFCCC in Kyoto in 1997 after hard negotiation, was rejected by the United States in early 2001, followed by Australia, saying the pact was too costly and unfairly exempted large rapidly industrializing countries such as China and India.[4] The agreement also has been vulnerable to strategic behavior. US withdrawal effectively gave Russia a veto power over entry into force, which it has used to extract concessions from the European Union and other countries. For example, Russia obtained additional credits from forestry in the Marrakech Accords agreed at COP7 in November 2001 and, according to the news by Reuters (November 18, 2004), it ratified the Protocol only in exchange for European Union agreement on terms for its admission to the World Trade Organization.

The emissions limitation commitments by industrialized countries under the Kyoto Protocol are not enough to prevent dangerous anthropogenic interference with the climate system.[5] US withdrawal made things worse. The emissions limitation commitments of the Annex I Parties to the Protocol could allow their aggregate 2008-2012

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[3] According to Article 25 of the Kyoto Protocol, it shall enter into force on the ninetieth day after the date on which not less than 55 Parties to the Convention, incorporating Parties included in Annex I which accounted in total for at least 55 percent of the total carbon dioxide emissions for 1990 of the Parties included in Annex I, have deposited their instruments of ratification, acceptance, approval or accession. Russia, which accounts for 17 percent of carbon dioxide emissions of Annex I countries in 1990, became the key to the entry into force of the Protocol after the United States, which accounts for 36 percent of Annex I emissions, pulled out of the Protocol.

[4] In February 2002, nearly a year after rejecting the Kyoto Protocol, President Bush unveiled a new approach on climate change. It includes a strategy to cut greenhouse gas intensity (ratio of emissions to GDP) by 18 percent over the next ten years. This proposal was severely criticized by environmental groups. World Resources Institute (2002) notes that the target is similar to the actual performance of the 1990s (16.9 percent reduction) and because of projected GDP growth, a emission intensity decline of this size actually implies 14 percent increase in the absolute level of emissions by 2012. It concludes that the President's goal is similar to past emission growth rates and will not, under any plausible scenario, actually reduce emissions.

[5] The ultimate objective of the Convention is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. This concentration level has not yet been agreed, but to stabilize the atmospheric concentration of greenhouse gases at any level will require significant reductions from current global emissions.

emissions to increase. This is because the surplus allocations to Russia and other eastern European countries may be large enough to meet the entire demand for emission reductions in the other industrialized country Parties to the Protocol.[6]

Den Elzen and de Moor (2001) shows the net reduction requirement from the Kyoto commitment decreases from 755 MtC (million tons of carbon) under the original agreement at the third Conference of the Parties (COP3) in Kyoto, to 115 MtC after the negotiation up to Marrakech Accords at COP7. Blanchard et al (2002) evaluates that the net reduction requirement would be negative and therefore the permit price in the market becomes zero due to over-supply. The market price of emission allowances or reduction credits could be kept above zero by Russia's banking of hot air into the second commitment period.[7] Russia is projected to have by far the largest supply of surplus allowances and so could increase the market price and its total revenue by limiting the quantity sold and banking the remainder of the allowances for future periods.

Table 1. Cost Estimates of Kyoto Commitment

Source	Scenario	Net Reduction (MtC)	Permit Price ($/tC)	Abatement Cost (mil 95$)
Den Elzen and de Moor (2001)	Original Kyoto Protocol	755	36	19,000
	Marrakech Accords	115	9	1,500
Blanchard et. al. (2002)	Original Kyoto Protocol	725	48	10,974
	Marrakech Accords	-183.5	0	0

6 In Russia and several other eastern European countries the emissions limitation commitment is higher than the projected emissions for 2008-2013 due to the significant economic declines they experienced during the early 1990s. In principle, the surplus allowances can be sold to other Annex I Parties and be used by them to meet their commitments. The difference between the emissions limitation commitment and the projected business as usual emissions is often called 'hot air'.

7 Den Elzen and de Moor(2001) shows the former Soviet Union countries' financial revenues from permit trading would be maximized by banking 40 to 70 per cent of the hot air. Haites(2004) indicates that Russia and the Ukraine can maximize their revenue by selling only about 40 % of their surplus assigned amount units (AAUs) and banking the remaining 60%.

The low environmental effectiveness of international environmental agreements is not unique to climate change, but a rather common characteristic of many such agreements. According to Finus and Tjotta (2003), abatement targets and annual net benefits under the Oslo Protocol are substantially lower than in the social optimum and even lower than in the Nash equilibrium. The social optimum is not stable and the maximal stable emission reduction only slightly exceeds that in the Nash equilibrium.[8] This protocol is only binding for seven (out of 33) countries with respect to the Nash equilibrium. Similar conclusions are presented for the Helsinki Protocol and the Montreal Protocol (Murdoch and Sandler, 1997a and 1997b).

One of the important characteristics of international environmental agreements is that there is no authoritative international judicial system. It is often claimed that because of this anarchy condition, international treaties must be self-enforcing. To be self-enforcing, an agreement must both be policed by the parties themselves and be enforceable by internal responses alone. According to this view, so-called external enforcement mechanisms (such as the use of trade sanctions to enforce a treaty on climate change) are incompatible with the notion of a self-enforcing agreement. (Hovi, 2002) Therefore, game-theoretic analysis based on behavioral assumption of self-interested players is quite useful to investigate these issues.[9]

The objectives of this study are to investigate plausible outcomes of climate change negotiation through a game-theoretic model, to interpret the discrepancies between the modeling outcome and the

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[8] Finus and Tjotta (2003) notes as follows: "This conclusion leaves us with a puzzling question: Why do states sign agreements specifying abatement obligations which they will meet or even overfulfill in their own interest anyway? We have no final answer yet. Nevertheless, we suggest the following possible explanations: first, environmentally conscious voters are rationally badly informed (given their marginal influence on election outcomes and the cost to obtain thorough background information about IEAs), whereas industry possesses private information about abatement costs and, given the importance of this interest group, holds a higher stake in the political system. Consequently, governments trying to capture political support have an incentive to accede to an IEA, to take on a relatively low abatement responsibility, and to later overfulfill their abatement targets, selling accession, and overfulfillment as good deeds to 'green voters', without imposing high cost on industry."

[9] Game theory is a mathematical analysis of multi-player decision-making processes where each player is assumed to maximize its own utility. Essential elements of a game are players, strategies, and payoffs. Players are the individuals who make decisions. Each player's goal is to maximize his utility by his choice of actions. Strategy is a rule that tells a player which action to choose at each instant of the game, given his information set. Payoff is the expected utility a player receives as a function of the strategies chosen by himself and the other players.

current situation, and to derive policy implications for improving the efficiency of the negotiations. Chapter 2 reviews the literature on game-theoretic research related to international pollution problems. Particular attention is paid to the coalition formation game in the context of climate change negotiation. Chapter 3 formulates the coalition formation game. Here we utilize the simulation model developed by Finus, Ierland and Dellink (2003). In Chapter 4, we analyze the outcome of negotiation with various scenarios on cooperation and interpret the results relative to the current negotiation situation. Chapter 5 summarizes the results and discusses policy implications and future research directions.

Chapter 2. Literature Review

It is a general conclusion of the literature that a public good (GHG emissions reduction effort in case of climate change mitigation) is under-provided due to the free rider effect and the free rider effect is more severe when the larger the number of players.

Like other public good problems, climate change mitigation poses a fundamental dilemma. Because most of the benefits of climate change mitigation do not accrue to the country taking action, but are shared by the international community as a whole, individual countries have little incentive to implement emission mitigation measures on their own. A country engaging in mitigation action receives only a fraction of the total benefits and can only justify incurring mitigation costs equal to the benefits it expects to receive.

At least from the theory, efficient provision of public goods can be implemented in dominant strategies as long as budget balance is not required. The idea is straightforward: Choose player *i*'s transfer (externality payments) so that player *i*'s payoff is the same as the total surplus of all players up to a constant. Because player *i* already internalizes his own surplus, it suffices to set the transfer equal to the total surplus minus his surplus. This is the Groves mechanism, which is well known from public good research. (Groves (1973); Clarke (1971)) It is, however, almost impossible to apply the mechanism to real world situations due to its lack of budget balance.

Lindahl (1919) suggests a useful equilibrium concept for public good economy. The *Lindahl equilibrium* is an equilibrium in an economy with perfect markets for all private goods and a special agency responsible for the provision of public goods. Given initial resources, one can associate with each Pareto optimum a vector of pseudo-prices (different price for the public good for each player) and lump sum transfers such that the given Pareto optimum can be reached as a competitive equilibrium with these pseudo-prices and transfers.

Kaneko (1977) verifies that the *Ratio equilibrium* (including the Lindahl equilibrium) belongs to the core of the voting game on the level of the public goods to be produced. An important implication is that if the equilibrium cost sharing ratio (which is proportional to

Lindahl prices) is known, the ratio equilibrium can be achieved by the voting game. We do not know, however, how to determine the equilibrium cost sharing ratio. This makes it difficult to apply Ratio equilibrium, or voting mechanism to achieve it, in practice.

Varian (1994b) describes two subsidy-setting games that yield Lindahl allocations in n-player games with general utility functions. Despite his strong assumption of complete information, the subsidy setting game provides a possibility of attaining Lindahl equilibrium by way of non-cooperative behavior. It is, however, necessary to ensure that all the players participate in the subsidy setting game. Even though every player is better off with this mechanism, some players can benefit more by not participating in the mechanism. This is the fundamental free-rider problem for public goods.

Barrett (1994) shows that self-enforcing international environmental agreements (IEAs), which establish rules for managing shared environmental resources, may not be able to improve substantially upon the non-cooperative outcome. Two different modeling approaches support this conclusion. The model of a self-enforcing IEA, which solves jointly for the number of signatories, the terms of the IEA, and the actions of non-signatories, shows that, depending on the functional specification, a self-enforcing IEA may not exist. Or it may not be able to sustain more than two or three signatory countries, in which case the IEA cannot increase global net benefits substantially when the number of countries that share the resource is large. The other model which takes the IEA to be an equilibrium to an infinitely repeated game, but one which is renegotiation-proof, shows that the full cooperative outcome can be sustained by a large number of countries, but only when the difference in global net benefits between the non-cooperative and full cooperative outcomes is small. When this difference is large, the full cooperative outcome can be sustained by only a few countries, or possibly none at all.

Carraro and Siniscalco (1993) analyses profitability and stability of international agreements to protect the environment in the presence of trans-frontier or global pollution. Each country decides whether or not to coordinate its strategy with other countries. A coalition is formed when conditions of profitability and stability are satisfied.[10] It is

[10] A coalition is defined to be profitable if the welfare of each country signing the

shown that such coalitions exist; that they tend to involve a fraction of the negotiating countries; and that the number of signatory countries can be increased by means of self-financed transfers. However, expanding coalitions requires some form of commitment. Such schemes of commitment and transfers can even lead to cooperation by all countries.

Finus, Ierland and Dellink (2003) empirically tests stability of climate change coalitions with the STAbility of COalitions model (STACO), which is utilized in our simulation analysis in Chapter 4. The model comprises twelve world regions and captures important dynamic aspects of the climate change problem. It applies the concept of internal and external stability to a cartel formation game.[11] Under the base case scenario, no coalition (among 4084 different coalition structures) is found to be stable both internally and externally. It is shown that only if benefits from global abatement are sufficiently high, do stable coalitions emerge, though they only marginally improve upon the Nash equilibrium.[12]

Eyckmans and Tulkens (2003) introduces The CLIMNEG world simulation (CWS) model[13] for simulating cooperative game theoretic aspects of global climate negotiations. With a numerical version of the (six-region) CWS model, the transfer scheme advocated by Germain et al. (1997)[14] induces an allocation in the ("gamma") core[15] of the world

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agreement is larger than the non-cooperative welfare. A coalition is stable if there is no incentive to defect for all countries belonging to the coalition (internal stability), and there is no incentive to broaden the coalition for all countries not belonging to the coalition (external stability).

[11] Internal stability means that no coalition member has an incentive to leave its coalition to become a singleton. External stability means that no singleton has an incentive to join a coalition.

[12] A Nash equilibrium is a profile of strategies such that each player's strategy is an optimal response to the other players' strategies. At a Nash equilibrium, no player has an incentive to deviate from the equilibrium. Most of equilibrium concepts, including the ones with stability, can be interpreted as Nash equilibrium in this sense. In this paper, we use Nash equilibrium as the Nash equilibrium of the game where there is neither cooperative commitment nor policy intervention. This is often called as 'laissez fair' or 'no-intervention' Nash equilibrium in the literature. It coincides with the singleton coalition structure in coalition formation games.

[13] In the CWS model each national economy is represented by a discrete time optimal growth model with a long but finite horizon. Growth is driven by exogenous population growth and technological change as well as by endogenous capital accumulation.

[14] The transfer scheme suggested by Germain et al. (1997) is a variant of the transfer scheme initially proposed by Chander and Tulkens (1995, 1997) in a static context, which is extended to a dynamic context. Essentially, the scheme consists in redistributing the surplus of cooperation over non-cooperation in proportion to the (marginal) climate change damage costs that countries experience. A mathematical representation of the

carbon emission abatement cooperative game.

Eyckmans and Finus (2003) uses the CWS model to analyze the formation of international environmental agreements (IEAs) by applying the widely used concept of internal and external stability and several modifications of it. They relax the assumptions of a single agreement and an open membership rule.[16] It turns out that regional agreements are superior to a single agreement and exclusive membership is superior to open membership in welfare and ecological terms. They compute payoff vectors for each of the six world regions under each of the 203 possible coalition structures over a time horizon of 350 years. Major conclusions are: 1) Neither the grand coalition, which is identical to the social optimum, nor the Kyoto coalition in its original (including USA) form or in its present form (without USA) are stable, regardless of the membership rule. Only coalitions with few members are stable. Nevertheless, in the context of climate change they can close the gap between no and full cooperation to a large extent. 2) Under exclusive membership more coalition structures are stable than under open membership and they are also superior in welfare and ecological terms. 3) Many stable coalition structures comprise multiple coalitions that are superior to a single coalition in welfare and ecological terms. The reason is that it is difficult to form one large coalition because of strong free-rider incentives but it is easier to form several small coalitions because interests within a coalition are more homogeneous. 4) Without transfers, countries with a similar incentive

scheme by Chander and Tulkens is provided in Chapter 3, which is applied in the scenario analyses in Chapter 4.

[15] An allocation belongs to the "gamma core" if it satisfies both individual rationality for all players and coalitional rationality for all possible coalitions. Individual rationality holds if every player is better-off compared to a Nash equilibrium and coalitional rationality holds if no coalition can find out that they can do better if the joint payoff of their members in the partial agreement Nash equilibrium (PANE) is higher than the efficient allocation. A partial agreement Nash equilibrium (PANE) wrote. S is a Nash equilibrium in which a coalition S coordinates its policies taking as given the strategies of the outsiders who, in turn, are playing a non-cooperative Nash strategy against S.

[16] Most of the analyses on stability have made two implicit assumptions. First, stability restricts coalition formation to only one (non-trivial) coalition. That is, countries have only the option to join an agreement or to remain a non-signatory (singleton) but cannot group into different agreements. The second assumption is that of open membership. That is, countries can join an agreement without the consent of existing members. Hence, it is easy for outsiders to upset a potentially stable coalition. From a theoretical point of view, some form of exclusive membership may help to stabilize IEAs. Currently all existing IEAs that deal with global environmental problems are of an open membership nature. However, other international institutions, such as NATO and WTO, require the consent of all their existing members before a newcomer can join.

structure in terms of marginal abatement and damage costs form coalitions. With transfers, contrasting interests can be balanced. This allows reaping efficiency gains from cooperation. The result supports the efforts in recent IEAs like the Kyoto and Montreal Protocol to raise participation of developing countries via compensation payments.

Carraro, Marchiori and Oreffice (2003) show that minimum participation rule is generally helpful to enhance the environmental effectiveness of an international agreement. Therefore, international environmental treaties should contain such a rule and this is actually the case for most existing treaties. Second, the optimal rule is generally coalition unanimity, in particular when the number of negotiating countries is not too large. However, two factors of information are crucial. First, the unanimity constraint is effective only if the profitability condition is met for all countries. Otherwise, it may be counterproductive. Therefore, in real agreements, a minimum participation unanimity rule should be associated with a transfer mechanism that makes the agreement profitable to all countries. Secondly, the curvature of the coalition's payoff function is also crucial. If benefits from cooperation do not increase with the number of cooperators, or increase too slowly, then it is not optimal to set a minimum participation constraint such that all countries must sign and ratify the treaty for it to enter into force.

Chapter 3. Formulation of Coalition Formation Game

Under a coalition game, each country decides unilaterally (non-cooperatively) whether or not to sign the environmental agreement (i. e. to join the coalition). Countries that sign the agreement play as a single player and divide the resulting payoff according to a given burden-sharing rule. The remaining countries play non-cooperatively against the coalition and against each other. The equilibrium outcome of a coalition game varies depending on the burden-sharing rule.

1. Formulation of a two-stage coalition formation game

Following Finus, Ierland and Dellink (2003), coalition formation is modeled as a *two-stage game*.[17] In the *first stage,* countries or regions decide simultaneously on their *membership* in a coalition. In the *second stage,* coalition members choose simultaneously their *abatement strategies*. It is assumed that there are no uncertainties and no information asymmetry. The possibility of multiple coalitions is also excluded in this paper.

Stage 1 of the Coalition Formation Game

In the *first stage,* we assume two membership strategies available to countries: strategy σ_i= 0 means "I do not want to sign the agreement" and σ_i = 1 means "I want to become a member of a climate treaty". Technically, this implies that countries that announce σ_i = 0 form a singleton coalition and those that announce σ_i = 1 become members of a non-trivial coalition (i.e., a coalition of at least two members).

Let i denote a particular country, $i \in I = \{1,\ldots,N\}$, and let a particular membership strategy of country i be the message σ_i and its

[17] Notations and definitions in this paper follow Finus, Ierland and Dellink (2003) except when new concepts are required.

strategy set be given by $\sum_i \{0,1\}$, $\sum = \sum_1 \times \sum_2 \times K \times \sum_N$ and denote I^S the set of countries that belong to a non-trivial coalition (set of signatories) and I^{NS} the set of countries that form a singleton coalition (set of non-signatories):

$$I^S = \{i | \sigma_i = 1, \exists j \neq i, \sigma_j = 1\}, I^{NS} = \{i | i \notin I^S\}$$

If $I^S = \varnothing$ it is called "*singleton coalition structure*" and if $I^s = I$ it is called "*grand coalition structure*".

Stage 2 of the Coalition Formation Game

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

$$\pi_i(q) = \sum_{t=1}^{T} (1+r_i)^{-t} (B_{it}(q_t) - AC_{it}(q_{it})) \qquad [1]$$

where T denotes the time horizon, t=1, ..., T, r_i is the discount rate of country i, B_{it}'s are benefits from global abatement, $q_t = \sum_{i=1}^{N} q_{it}$, AC_{it}'s are abatement costs from individual abatement and q is an abatement vector of dimension $N \times T$. (q_{it} is the amount of emission abatement by country i in time t) Benefits from global abatement are derived from reduced environmental damages caused by greenhouse gas emissions.

We make the standard assumption: $\forall\ i \in I, q_{it} \in [0, e_{it}^{BAU}]$ " and at each time t: $B_{it}^{'} > 0, B_{it}^{''} \leq 0, AC_{it}^{'} > 0$ and $AC_{it}^{''} > 0$ where primes denote first and second derivatives and e_{it}^{BAU} is the emission level in the business-as-usual scenario.

Assume that signatories $i \in I^S$ jointly maximize the aggregate payoff to their coalition I^s and each non-signatory $j \in I^{NS}$ maximizes his own payoff ($I^{NS} \cap I^S = \varnothing$, $I^{NS} \cup I^S = I$). Let q^S denote the abatement strategy vector of signatories and q_j^{NS} the abatement strategy vector of a non-signatory j, $q_i \in Q_i, Q = Q_1 \times K \times Q_N$, and assume that the equilibrium abatement vector $(q^{S*}, q^{NS*}) = q^* = (q^{S*}, q^{I \setminus I^{S*}}) = (q_j^*, q^{I \setminus j*})$ satisfies:

$$\forall q^S \in Q^S : \sum_{i \in I^S} \pi_i(q^{S*}, q^{I \setminus I^{S*}}) \geq \sum_{i \in I^S} \pi_i(q^S, q^{I \setminus I^{S*}}) \text{ and}$$

$$\forall j \in I^{NS}, \forall q_j \in Q_j : \pi_j(q_j^*, q^{I \setminus j^*}) \geq \pi_j(q_j, q^{I \setminus j^*}),$$

where q^* is assumed to be a unique interior equilibrium.

2. Stability of coalitions with transfers and commitments

We call a coalition structure { I^S, I^{NS} } stable if no signatory has an incentive to leave the agreement (internal stability) and no non-signatory has an incentive to join the agreement (external stability).

Let the value to country *i* in coalition structure { I^S, I^{NS} } generated by announcement σ under transfer function *T* be

$v_i(\sigma) = \pi_i(q^*) + T_i(\sigma)$, where $\sum T_i(\sigma) = 0$.

A coalition structure { I^{S*}, I^{NS*} } generated by σ^* is called

internally stable

if $\forall i \in I^{S*} : v_i(\sigma_i^* = 1, \sigma_{-i}^*) \geq v_i(\sigma_i = 0, \sigma_{-i}^*)$, and

externally stable

if $\forall j \in I^{NS*} : v_j(\sigma_j^* = 0, \sigma_{-j}^*) \geq v_j(\sigma_j = 1, \sigma_{-j}^*)$

There are many possible transfer functions (for coalition I^S).[18] We consider three transfer scenarios: no transfer, Chander-Tulkens transfer and the Shapley value.

The transfer scheme by Chander and Tulkens (1995, 1997) (CT scheme hereafter) redistributes the surplus of cooperation over non-cooperation in proportion to the marginal climate change damage (MD_i) that countries experience. CT scheme is compatible with a Lindahl equilibrium, where each agent faces a personalized price which corresponds to its marginal benefit, for the public good. For international environmental agreements, proportionality with regard to damages has been advocated not only for its strategic stability properties, but also for incentive compatibility reasons (Eyckmans, 1997). We can formulate the CT transfer as follows:

$$T_i = -(\pi_i(q^*(I^S)) - \pi_i(q^*(\varnothing))) + \frac{MD_i}{\sum_{j \in I^S} MD_j} \left(\sum_{j \in I^S} (\pi_j(q^*(I^S)) - \pi_j(q^*(\varnothing)))\right),$$

[18] Possible alternatives include solution concepts from in cooperative game theory such as Nash bargaining solution, Nucleolus, and surplus sharing schemes based on Lindahl equilibrium, such as Chander-Tulkens transfer scheme. The Nucleolus is excluded in our analysis due to its computational complexity. The Nash bargaining solution was applied in our analysis but the result is not explained since no meaningful outcome (non-trivial stable coalition) has need found.

for $i \in I^S$, where $q^*(\emptyset)$ is the equilibrium abatement vector for the singleton coalition structure ($I^S=\emptyset$).

The proportional transfer scheme results in an allocation in the core of a cooperative emission abatement game. This core property is a necessary (but not sufficient) condition for full, voluntary cooperation among the countries involved as explained in Tulkens (1998). If it is not satisfied, coalitions of countries can obtain a better outcome by coordinating their emission strategies among themselves and such coalitions have no incentive to join a worldwide environmental treaty (Eyckmans and Tulkens (2003)).[19]

The third transfer scenario for our analysis assumes transfers according to the Shapley value defined as follows:

$$v_i(c(\sigma)) = \sum_{w \subseteq I^S - i} \frac{|w|! \cdot (|I^S| - |w| - 1)!}{|I^S|!} (\pi(q^*(w \cup \{i\})) - \pi(q^*(w))),$$

for $i \in I^S$, where $q^*(w)$ is the equilibrium abatement vector for the coalition composed of w, which is a subset of countries.

Shapley (1953) presented the value as an operator that assigns an expected marginal contribution to each player in the game with respect to a uniform distribution over the set of all permutations on the set of players.[20] Specifically, let p be a permutation (or an order) on the set of players and let us imagine the players appearing one by one to collect

19 There are several mechanisms proposed to implement cooperative outcomes under CT transfer. Varian (1994) suggests two subsidy-setting games that yield Lindahl allocations in n-person public good games with general utility functions. He shows that under two-player game, if each agent chooses the rate at which he will subsidize the other agent's contributions (emissions reduction in our case), the subsidies that support the Lindahl allocation are the unique equilibrium outcome. When there are more than two players, he designs the rule under which agent 1 sets the rate at which agent 2 will subsidize agent 3's contributions and agent 2, in turn, sets the rate at which agent 3 will subsidize 1's contributions, and so on. He also suggests another two-stage mechanism for implementing Lindahl allocations. At the price-setting stage, each agent announces a price. The price for each agent's contribution to the public good is the average of the prices named by all the other agents. At the contribution stage, each agent chooses the contribution to maximize his payoff with the penalty term which is an increasing function of the difference between the sum of the prices and the sum of marginal benefits. Eyckmans (1997) also suggests a similar kind of two-stage financial compensation mechanism that implements a proportional cost sharing solution in complete information Nash equilibrium.

20 The explanation on the Shapley value in this section is adapted from Winter (2002) with some modification.

their payoff according to the order *p*. For each player *i* we can denote by $o_p^i = \{j : p(i) > p(j)\}$ the set of players preceding player *i* in the order *p*. The marginal contribution of player *i* with respect to that order *p* is $v(o_p^i \cup i) - v(o_p^i)$ where $v(S)$ represents the total payoff the coalition S can get in the game. If permutations are randomly chosen from the set of all permutations, with equal probability for each one of the *n*! permutations, then the average marginal contribution of player *i* in the game is the Shapley value. The Shapley value has been used quite often as a practical tool for the measurement of political power and cost allocation.[21]

Of all the solution concepts in cooperative game theory, the Shapley value is arguably the most "cooperative", undoubtedly more so than such concepts as the core and the bargaining set whose definitions include strategic interpretations. Yet, perhaps more than any other solution concept in cooperative game theory, the Shapley value also emerges as the outcome of a variety of non-cooperative games with quite different structures and interpretations.[22]

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[21] While the intuitive definition of the value speaks for itself, Shapley supported it by an axiomatic characterization with four axioms. The first axiom (efficiency) requires that players precisely distribute among themselves the resources available to the grand coalition. The second axiom (symmetry) requires that symmetric players have symmetric values. The third axiom (dummy) requires that zero payoffs be assigned to players whose marginal contribution is null with respect to every coalition. Final axiom (additivity) requires that the value be an additive operator on the space of all games. Shapley (1953) shows that there exists a unique value satisfying the efficiency, symmetry, dummy, and additivity axioms and it is the Shapley value.

[22] Winter (1994) describes a bargaining situation where players submit demands, i.e., players announce the share they request in return for cooperation. A coalition emerges when the underlying resources are sufficient to satisfy the demands of all members. As an example, consider the order in which players move according to their name, i.e., player 1 followed by 2, etc. Each player *i* in his turn publicly announces a demand d_i (which should be interpreted as a statement by player *i* of agreeing to be a member of any coalition provided that he is paid at least d_i). Before player *i* makes his demand, we check whether there is a compatible coalition among the *i*-1 players who have already made their demands. A coalition *S* is said to be compatible (to the underlying game *v*) if *S* can satisfy the demands of all its members, i.e., $\Sigma_{j\in S}\ d_j \le v(S)$. If compatible coalitions exist, then the largest one (in terms of membership) leaves the game and each of its members receives his demand. The game then proceeds with the set of remaining players. If no such coalition exists, then player *i* moves ahead and makes his demand. The game ends when all players have made their demands. Those players who are not part of a compatible coalition receive their individually rational payoff. Consider now a game that starts with a chance move that randomly selects an order with a uniform probability distribution over all orders and then proceeds in accordance with the above protocol. We call this game the demand commitment game and Winter (1994) shows that the demand commitment game implements the Shapley value. Dasgupta and Chiu (1998) discuss a modified version of the Winter (1994) game, which allows for the implementation of the Shapley value in general games.

In real-world negotiations, indicators such as population, per capita GDP, and historic emissions may be more compelling criteria for burden sharing or the transfer mechanism. During the negotiation process leading to the Kyoto Protocol, a wide range of indicators had been proposed by Parties for burden sharing, including GHG emissions, per capita emissions, emissions per GDP, per capita GDP, cumulative emissions, population growth rates. The final result of the negotiation on commitments, however, is not related in any systematic way to these criteria, although some weak relationship can be argued.[23] This shows that the outcome of real-world negotiation depends mostly on political bargaining, rather than principles of equity.

Together with transfer scenario, we apply a scenario of commitment under which the countries belonging to the stable coalition commit to cooperation. A stable coalition can be expanded by transfers to non-cooperating countries, provided some form of commitment takes place. Carraro and Siniscalco (1993) proposed four types of commitments in this regards as follows:

i) The countries belonging to the stable coalition commit to cooperation (stable coalition commitment)

ii) The countries belonging to the stable coalition commit to cooperation and any new signatory as soon as it enters the expanded coalition, must commit to cooperation as well (sequential commitment)

iii) The number of committed countries is such that appropriate transfers can induce all the other countries to cooperate (full-cooperation minimum commitment)

iv) A subset of non-cooperating countries commits to transfer

[23] The emission caps of Annex I Parties were assigned in Kyoto through a process of political negotiation. A variety of objective criteria were proposed, including those indicated in the above. However, negotiators failed to agree on which criteria to use, with most countries supporting whichever would grant them a more lenient target. (Depledge, 2002) Several studies analyze the relationship between the burden of emission reduction requirement in the Kyoto Protocol and some of indicators proposed in the negotiation process. OECD(1999) estimates the correlation coefficient between the reduction burden and the per capita GDP to be 0.42, while Korea Environment Institute (2002) estimates it to be 0.55. The difference between the two studies stems from the difference of data sets on business-as-usual forecasts. Both of the studies, however, conclude that per capita GDP, if any, seemed to be the most prominent factor among the indicators considered that might have influenced the negotiation process.

welfare in order to induce the remaining non-signatories to cooperate, and to guarantee the stability of the resulting coalition (external commitment)

We apply 'stable coalition commitment' for our empirical analysis. It is necessary to impose a constraint on the amount of transfers allowed: Transfers must be self-financed, i.e. the total transfer must be lower than the gain that the committed countries obtain from expanding the coalition. The purpose of the analysis is to assess the scope of the potential to improve the coalition with the commitment. In most of international environmental agreements, industrialized countries take commitments that are stronger and earlier than developing countries, as is the case of climate change. We will see the potential effects of this kind of regime on the efficiency of the coalition, particularly the number of cooperating countries.

3. Empirical data for simulation analysis

In this study, we apply the empirical model (STACO) by Finus, Ierland and Dellink (2003) which is based on emission reduction cost estimates by Ellerman and Decaux (1998) and damage costs estimates by Fankhauser (1995) and Tol (1997).[24] Among the many kinds of simulation models in the literature, it seems to be most appropriate for our analysis. It encompasses both the benefit (damage from climate change) and cost (greenhouse gas reduction cost) side information in a coherent way and it includes most of the influential players in the climate change negotiation such as United States, European Union, China, India, OPEC, Japan, Brazil and the former Soviet Union. The sufficient number (12) of separated regions (country or a group of countries) is also an advantage for a game model analysis to reflect the free-rider incentive inherent in global environmental problems, which is significantly more serious with more players.

In view of the great uncertainties inherent in the climate change problem, any cost and benefit estimates and any simulation results based on them need careful interpretation.

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[24] See the Appendix for a detailed explanation.

The STACO model has twelve world regions[25] that give rise to 4,096 possible coalition structures. Since a strategy vector where only one region announces σ_i = 1 (cooperate) and all other regions announce σ_i = 0 (do not cooperate) leads to the same coalition structure as if all regions announce σ_i = 0, there are 4,084 different coalition structures.

Each region (Region *i*) has a *benefit function* (benefit of reduced climate change damages) $TB_i(q) = s_i \cdot TB(q)$, where the global benefit $TB(q) = 37.40 \cdot q$. Each region (Region *i*) has an annual abatement cost function $AC_i(q_i) = (1/3) \cdot \alpha_i \cdot (q_i)^3 + (1/2) \cdot \beta_i \cdot (q_i)^2$. The total *abatement cost* of region *i* is $TAC_i(q_i) = AC_{it}(q_i) \cdot \sum_{t=2011}^{2110} (1+r)^{-(t-2010)}$, where discount rate (*r*) is 2 percent. Region *i* has *payoff function* $\pi_i = TB_i(q) - TAC_i(q_i)$.[26]

Table 2. Benefit and Abatement Cost Parameters

Region	Emission in 2010(Gton)	Share of global benefits s_i	Abatement cost Parameter β_i	Abatement cost Parameter α_i
1. USA	2.42	0.226	0.0005	0.00398
2. JPN	0.56	0.173	0.0155	0.18160
3. EU	1.4	0.236	0.0024	0.01503
4. OOE	0.62	0.035	0.0083	0
5. EET	0.51	0.013	0.0079	0.00486
6. FSU	1	0.068	0.0023	0.00042
7. EEX	1.252	0.030	0.0032	0.03029
8. CHN	2.36	0.062	0.00007	0.00239
9. IND	0.63	0.050	0.0015	0.00787
10.DAE	0.41	0.025	0.0047	0.03774
11.BRA	0.13	0.015	0.5612	0.84974

25 The twelve regions are: USA (denoted as USA), Japan (JPN), European Union (EEC), other OECD countries (OOE), Eastern European countries (EET), former Soviet Union (FSU), energy exporting countries (EEX), China (CHN), India (IND), dynamic Asian countries (DAE), Brazil (BRA) and the rest of the world (ROW). See the appendix for detailed information.

26 The assumption of a 2% discount rate yields a global emissions reduction under the grand coalition (21.4% of 2010 emissions) that is much smaller than needed to stabilize atmospheric concentrations. A lower discount rate is likely to lead to a larger emissions reduction. Weitzman (2001) argues for a declining discount rate (“Gamma Discounting”) for issues, such as climate change, with very long time horizons. We should be careful in interpreting analysis based on such an assumption and need to do sensitivity analysis with regard to discount rates, which is remained for future research, for a more general conclusion.

12.ROW	0.7	0.068	0.0021	0.00805
WORLD	11.96	$\sum s_i = 1$		

Source: Finus, Ierland and Dellink (2003)

Chapter 4. Results and Discussion

1. Singleton Coalition and Grand Coalition

Under the singleton coalition structure, each region chooses its emission reduction level to maximize its own net benefit (benefit minus cost) and therefore reduces its emissions to the level at which its marginal abatement cost equals its own marginal benefit. The global emission reduction over 100 years is 55 Gton (giga ton = billion ton) and the annual emission reduction is about 4.6% of the 2010 emissions. The global net benefit over 100 years is estimated to be US$1,960 billion.

Regions with higher marginal benefits, such as United States (USA) and EU (EEC), and those with lower abatement costs, such as the former Soviet Union (FSU), China (CHN), India (IND) and the rest of the world (ROW), make larger reductions than the other regions.

Table 3. Singleton Coalition Structure (Nash Equilibrium)

Region	Total emission reduction	Annual emission reduction	Total abatement costs	Total benefits from abatement	Benefits minus abatement costs	Marginal abatement costs	Marginal benefit
	Gton(over 100years)	% of emissions in 2010	Bln US$ over 100years			US$/ton	
USA	16	6.7	53	468	415	8.5	8.5
JPN	1	1.4	2	357	354	6.5	6.5
EEC	7	4.7	24	488	464	8.8	8.8
OOE	2	3.1	1	71	71	1.3	1.3
EET	1	1.8	0	27	27	0.5	0.5
FSU	5	4.9	4	140	135	2.5	2.5
EEX	1	0.7	0	62	62	1.1	1.1
CHN	15	6.6	16	128	112	2.3	2.3
IND	3	5.3	3	103	101	1.9	1.9
DAE	1	1.3	0	52	51	0.9	0.9
BRA	0	0.1	0	32	32	0.6	0.6
ROW	4	5.3	4	141	137	2.5	2.5
World	55	4.6	109	2,069	1,974		37.4

Under the grand coalition structure, all regions implement the emission reduction needed to maximize the global net benefit (sum of net benefits of all regions). This requires each region to reduce its emissions to the level at which its marginal abatement cost equals the global marginal benefit (sum of marginal benefit of all regions). The global emissions reduction is 256 Gton over 100 years and the annual emissions are about 21.4% lower than in 2010. The global net benefit becomes US$ 6,031 billion, over three times the net benefit of the singleton coalition.

The regions with low abatement costs and low marginal benefits, such as the energy exporting countries (EEX) and China, face negative net benefits under the grand coalition. This shows that the grand coalition does not satisfy the individual rationality and stability conditions and indicates that a transfer scheme is needed to induce those regions to cooperate.

Table 4. Grand Coalition Structure (Social Optimum)

Region	Total emission reduction	Annual emission reduction	Total abatement costs	Total benefits from abatement	Benefits minus abatement costs	Marginal abatement costs	Marginal benefit
	Gton (over 100years)	% of emissions in 2010	Bln US$ over 100years			US$/ton	
USA	38	15.7	513	2169	1656	37.4	8.5
JPN	4	6.5	63	1653	1590	37.4	6.5
EEC	16	11.5	229	2262	2033	37.4	8.8
OOE	10	16.5	127	331	203	37.4	1.3
EET	10	19.6	130	125	-6	37.4	0.5
FSU	19	19.3	242	647	405	37.4	2.5
EEX	12	10.2	188	288	99	37.4	1.1
CHN	96	40.6	1348	594	-754	37.4	2.63
IND	22	33.8	295	479	184	37.4	1.9
DAE	10	25.1	155	239	84	37.4	0.9
BRA	1	5.5	12	147	135	37.4	0.6
ROW	19	26.5	250	652	401	37.4	2.5
World	256	21.4	3,553	9,584	6,059		37.4

2. Stable Coalitions without Commitments

We analyses stable coalition structures under the three transfer schemes: no transfer, CT scheme, Shapley value. Under 'no transfer' scenario, no non-trivial coalitions are stable. We checked all 4,084 possible coalition structures but found no stable coalition structure that is internally and externally stable at the same time, except the singleton coalition structure. While more than 1,000 coalition structures are externally stable, only 14 coalition structures are internally stable and these are not externally stable. This result has already been shown by Finus, Ierland and Dellink (2003) and motivates the analysis of transfer schemes in this study.[27]

Under 'CT scheme', two coalition structures are internally and externally stable: {USA, CHN}, {EEC, CHN}. The global net benefit over 100 years is US$ 2,969 billion ({USA, CHN}) and US$ 2,958 billion ({EEC, CHN}). These CT coalitions achieve about one fourth of the maximum potential gain from cooperation.[28]

Table 5. Stable Coalitions under CT transfer

USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW	Global
Net Benefit												
528	566	749	114	43	219	98	143	161	82	49	216	2,969
686	564	585	114	42	218	98	144	161	82	49	215	2,958
Amount of Transfer												
-137	0	0	0	0	0	0	137	0	0	0	0	-
0	0	-149	0	0	0	0	149	0	0	0	0	-

* Participants in coalitions are indicated by shaded cells. The net benefits include the transfers.

[27] Two more transfer scenarios were simulated in this study: One is the transfer according to Nash bargaining solution and the other is sharing of benefits proportional to the additional contribution of each region compared to the coalition without the region. Neither of these transfer rules sustain a stable coalition.

[28] The maximum potential gain from cooperation is US$4,085 (= US$ 6,059 (for the grand coalition) – US$ 1,974 (for the singleton coalition)). The gain achieved by the T coalitions is US$ 995 (= US$ 2,969 for {USA, CHN} – US$ 1,974 (for the singleton coalition)). This represents 24.3% (=995/4,085) of the maximum potential gain from cooperation.

This result implies that a welfare transfer mechanism can play an important role in promoting cooperation to resolve international environmental problems. The potential to improve global welfare through cooperation induced by welfare transfers, however, is quite limited. The CT coalitions consist of only two regions even though there are twelve regions in the world. However, the coalitions involve the largest emitters and so cover 31.4% {EEC, CHN} to 40.0% {USA, CH N} of 2010 global emissions.

Both stable coalitions contain one region with low mitigation costs and low marginal benefit (China) and another with high mitigation cost and high marginal benefit (United States or European Union). The low cost, low marginal benefit region contributes a large emission reduction, while high cost, high marginal benefit region benefits through reduced climate change damage as a result of the emission reductions in the other region. A welfare transfer scheme promotes coalitions composed of regions with very different characteristics. The welfare transfer over 100 years is US$ 137 billion in {USA, CHN} and US$ 149 billion in {EEC, CHN}, and it is transferred to China (CHN) from United States (USA) or European Union (EEC). The welfare transfer makes China, as well as United States or European Union, better off than under the no-cooperation Nash equilibrium. China would be worse off without the welfare transfer and would not participate in the coalitions.

Another interesting fact is that either the United States or the European Union participates in the coalition, but not both. When one of these regions participates in a coalition, the other does not because it gets a higher payoff by staying outside the coalition than by creating a three-region coalition. Moreover, each of these regions gets a higher payoff from being outside the coalition than being part of the coalition. For example, the United States gets $528 billion as part of the coalition {USA, CHN} but $686 billion under {EEC, CHN} coalition. Therefore, United States may want European Union to form a coalition with China and European Union may want United States to form a coalition with China. The United States and European Union each have an incentive to wait for the other to form a coalition with China and, as a result, a coalition may never be formed even though each would benefit from being part of such a coalition.

The three regions, the United States, the European Union and China, are the most important and influential players in the climate change negotiation. They are the three biggest emitters in the world, accounting for 51.7% of the global emissions in 2010. And the United States and the European Union are the two highest income regions, representing 56.2% of world GDP in 2010.

Table 6. Basic statistics for twelve regions in STACO model (for 2010)

Region	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW	Global
Emissions (Gton)	2.42	0.56	1.40	0.62	0.51	1.00	1.22	2.36	0.63	0.41	0.13	0.70	11.96
Share (%)	20.23	4.68	11.71	5.18	4.26	8.36	10.20	19.73	5.27	3.43	1.09	5.85	100.00
Income (billion $)	8,845	5,584	9,579	1,902	405	501	1,650	1,021	458	972	774	1,119	32,810
Share (%)	26.96	17.02	29.20	5.80	1.23	1.53	5.03	3.11	1.40	2.96	2.36	3.41	100.00
Population (million)	305	124	375	142	120	287	1,602	1,340	1,145	207	190	584	6,421
Share (%)	4.75	1.93	5.84	2.21	1.87	4.47	24.95	20.87	17.83	3.22	2.96	9.10	100.00

Source. Weikard, Finus and Altamirano-Cabrera (2004)

When the transfers are calculated on the basis of the Shapley value, there are more stable coalitions that induce more regions and generate a larger global net benefit than with CT transfers. Shapley value transfers sustain three stable coalition structures, each of which is composed of three member regions: {USA, EET, CHN}, {JPN, EET, CHN} and {EEC, EET, CHN}. {USA, EET, CHN} gives the highest global net benefit, US$ 3,164, which is 6.5% greater than the highest net benefit for a coalition with CT transfers, US$ 2,969. The Shapley value coalitions achieve 23.3% to 29.1% of the maximum potential gain from cooperation and cover 28.7% to 44.2% of 2010 global emissions.

Table 7. Stable Coalitions under Shapley value transfer schemes

Region	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW	Global
Net Benefit													
S-1	506	607	805	122	46	235	105	193	173	88	53	232	3,164
S-2	669	413	729	111	41	213	95	163	157	80	48	210	2,929
S-3	738	603	560	122	47	234	105	198	172	87	53	231	3,148
Amount of Transfer													
S-1	-207	0	0	0	22	0	0	185	0	0	0	0	-
S-2	0	-135	0	0	15	0	0	120	0	0	0	0	-
S-3	0	0	-226	0	24	0	0	202	0	0	0	0	-

* Participants in coalitions are indicated by shaded cells. Net benefits include transfers.

The Shapley value coalitions all include China and Eastern European Countries (EET) as recipients of transfer payments from the United States, the European Union, or Japan. China gets larger transfers than under the CT rule and so has a higher net benefit. Since the EET also gets transfers the net benefit to the USA, EEC or JPN is lower than under the CT rule.

The Shapley value coalitions also provide higher net benefits for the USA, EEC and JPN if they are outside a coalition formed by one of the other regions. Thus although each region benefits from being part of a coalition, it also has an incentive to wait for one of the others to form a coalition.

The broader participation under the Shapley value transfer leads to the conjecture that this might be a useful burden-sharing mechanism to create stable coalition. The reason for this outcome may be the success of Shapley's concept as a measure of the political power of the players, which enables them to agree on a more efficient political deal in practice. The Shapely value is one of the concepts that is applied quite often in practice to measure political power and cost allocation. Generalization of this argument needs further research.

One interesting observation from the above results is that China is always part of the coalition. Due to its low marginal abatement cost, China is an attractive partner in any stable coalition. Any coalition without China yields only a small potential benefit to be shared among member regions. The key implication is that China needs to be involved in a coalition, which requires a sufficient transfer of welfare from the industrialized regions to make it better off than not participating.

A similar result is obtained by Weikard, Finus and Altamirano-Cabrera (2004). They use the STACO model to compare different burden sharing rules like grandfathering (i.e. sharing proportional to emissions in the past) and a number of so-called equitable rules like, sharing based on population or historical responsibility. They show that China is always part of the stable coalition except for the extreme case of inverse emissions.[29]

Weikard, Finus and Altamirano-Cabrera (2004) finds that the use of egalitarian, population, ability-to-pay and inverse emission transfer rules are not very effective in creating stable coalitions that produce a significant share of the maximum potential gains from cooperation.[30] Transfers based on abatement cost yields mixed results. Sharing the net gains according to regional income or damages captures about one fourth of the maximum potential gains from cooperation with two-region coalitions similar to those obtained with the CT transfer rule. The best results are obtained when the gains due to cooperation are divided according to base-year emissions (grandfathering). The stable coalition found for that case comprises the USA, EET, EEX and CHN and achieves about 35% of the maximum potential gains from cooperation. This four-region coalition is the only case that has a higher global net benefit than those in our analysis. In other words, the grandfathering rule can sustain a larger stable coalition than the CT or Shapley transfer rule.

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[29] Under the inverse emissions burden sharing rule, each region's share of the gains from cooperation varies inversely with its share of global emissions. This rule reflects historical responsibilities.

[30] Under egalitarian claims, all regions have equal claims for benefit sharing. Population claims distributes the benefit of a coalition in proportion to individual member regions and under the ability-to-pay claims, regions with a lower per capita income has a larger share of net benefits.

Table 8. Stable Coalitions under Various Surplus Sharing Rules

Sharing Scheme (benchmark case)	Members of coalition	Global annual emissions reduction	Global abate-ment costs	Global benefits	Global net benefits	Coalition surplus + external benefit	Benefits relative to grand coalition
		Mton		bln US$ over 100 years			%
(Singletons)*		553	109	2,069	1,960	0+0	0.0
(Grand coalition)*	All regions	2,563	3,553	9,584	6,031	4,071+0	100.0
Egalitarian	EET, CHN, IND	711	159	2,658	2,499	22+516	13.2
Regional income	EEC,CHN	870	311	3,253	2,942	151+831	24.1
Population	EEX,CHN	620	127	2,317	2,190	4+226	5.7
Ability-to -pay	EET, FSU, CHN	731	172	2,735	2,563	32+571	14.8
	EET, EEX, CHN	665	140	2,485	2,346	12+374	9.5
	EET, CHN, IND	711	159	2,658	2,499	22+516	13.2
Emissions	USA, EET, EEX,, CHN	1,030	436	3,854	3,418	264+1,194	35.8
Inverse emissions	EET,BAR	559	109	2,090	1,981	0.2+21	0.5
	CHN,BRA	582	116	2,176	2,059	1+98	2.4
Damage cost	USA,CHN	874	314	3,270	2,956	142+854	24.5
	EEC,CHN	870	311	3,253	2,942	151+831	24.1
Abatement cost	USA,CHN	874	314	3,270	2,956	142+854	24.5
	JPN,CHN	796	237	2,976	2,739	85+694	19.1
	OOE,CHN	626	129	2,341	2,212	6+246	6.2
	FSU,CHN	683	154	2,553	2,398	17+421	10.8
	EEX,CHN	620	127	2,317	2,190	4+226	5.7
	CHN,IND	662	143	2,477	2,334	11+363	9.2
	CHN,LOW	683	155	2,555	2,400	17+423	10.8

* The benchmark cases are not stable coalition structures. The global net benefits for the singleton and grand coalition cases are slightly different than those shown in Tables 3 and 4 because the cost and benefit parameters used in our analysis (Table 2) is rounded off to smaller digits.

Source. Weikard, Finus and Altamirano-Cabrera (2004)

It is important to note that many burden sharing rules advocated on the basis of equity, such as egalitarian, regional income, population, ability-to-pay, inverse emissions (historical responsibility), tend to result in inefficient outcomes in the framework of stable coalition formation games. The grandfathering rule, however, offers the possibility of a better outcome than the CT and Shapley value transfer schemes and deserves to be investigated further in future research.

3. Stable Coalitions under Commitments

This section analyzes stable coalition structures under commitments. Under the commitment scenario, a group of regions forms a stable coalition and induce, through appropriate transfers, other regions to join the coalition ('stable coalition commitment' in Carraro and Siniscalco (1993)). The member (committed) regions are assumed to transfer all of the potential increase in welfare to the non-member regions as an inducement to join the coalition. The non-member regions that are induced to join the coalition (new members) share the welfare gains, which are composed of the welfare increase from the coalition expansion accruing to the new members and of the transfer from the initial coalition members (now with commitments), according to the CT or Shapley value transfer rules.

The analysis is limited to two cases: One is to expand the stable coalitions under the CT transfer rule by making transfers to new members using the CT scheme. The other is to expand the stable coalitions under Shapley value transfer by making transfers to new members using the Shapley value rule.

The CT transfer rule yielded two stable coalitions ({USA, CHN} and {EEC, CHN}) each composed of two member regions. For each of these two stable coalitions, the stability of adding any combination of the ten non-member regions is checked, a total of 1,014 cases (= 1,024 (=10!) -10) for each stable coalition. Likewise, for each of the three stable coalitions under Shapley value transfer rule, each consisting of three members, the stability of adding any combination of the nine non-members is checked, a total of 503 cases (= 512 (=9!) –9).

The stability condition in the commitment scenario is modified as follows. For regions with commitments, each of which is a member in initial stable coalition, stability is not checked again in the enlarged coalitions formed by commitment and transfer. Stability is checked only for new members induced to join the committed coalition members. The internal and external stability conditions are checked for every new member by comparing its new payoff after coalition expansion with its payoff under a coalition without itself.

Under the 'stable coalition commitment' scenario with CT transfer, four coalitions are found to be stable: One ({USA, EEC, CHN, IND}) is an expansion of the {USA, CHN} coalition and the other three ({USA, EEC, FSU, CHN}, {USA, EEC, CHN, IND}, {USA, EEC, CHN, ROW}) are formed from the {EEC, CHN} coalition. The United States, European Union and China are the common members of all four enlarged coalitions. Each of the enlarged coalitions includes India (IND), the former Soviet Union (FSU), or the rest of the world (ROW) as its fourth member. The coalition {USA, EEC, CHN, IND} can be formed starting from either {USA, CHN} or {EEC, CHN}. The payoffs to the four member regions are, however, different depending upon the initial coalition: In the former case, USA pays the EEC to join so EEC's payoff is much higher than in the latter case.

Table 9. Stable Coalitions with commitment under CT transfer

	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW	Global
Participation	1	0	2	0	0	0	0	1	2	0	0	0	
Net benefit (billion US$)	528	895	1,050	181	67	348	155	143	225	129	78	344	4,145
Participation	2	0	1	0	0	2	0	1	0	0	0	0	
Net benefit (billion US$)	969	892	585	180	67	303	155	144	256	129	78	342	4,100
Participation	2	0	1	0	0	0	0	1	2	0	0	0	
Net benefit (billion US$)	990	895	585	181	67	348	155	144	228	129	78	344	4,145
Participation	2	0	1	0	0	0	0	1	0	0	0	2	
Net benefit (billion US$)	971	893	585	180	67	347	155	144	256	129	78	300	4,105

* In 'Participation' rows, '1' indicates the initial stable coalition members with commitment, '2' indicates new members subsidized by the members with commitment and '0' indicates non-members.

The global net benefit ranges from US$ 4,100 to US$ 4,145 with the highest value being realized by {USA, EEC, CHN, IND}. The enlarged coalitions achieve 52.0% to 53.1% of the maximum potential gain from cooperation and cover 56.9% to 60.0% of 2010 global emissions. The enlarged coalitions more than double the share of the potential gains achieved and increase the share of global emissions covered by 20 to 25 percentage points, thus they represent a significant expansion of the climate change agreement.

The ‘stable coalition commitment’ scenario with Shapley value transfer yields ten enlarged coalitions ranging in size from seven to nine regions. Four of the coalitions are enlargements of the {USA, EET, CHN} coalition and three each are enlargements of the {EEC, EET, CHN} and {JPN, EET, CHN} coalitions. Two coalitions can be formed starting from {USA, EET, CHN} or {EEC, EET, CHN} although the distribution of net benefits differs with the starting coalition.

Japan participates only in the coalitions where it is a member of the founding committed coalition; it does not join a coalition that involves the USA or EEC initially. The three enlarged coalitions that include Japan cover a substantially smaller share of 2010 global emissions (61.8% to 67.8%) and substantially smaller share of the maximum potential gain from cooperation (65.7% to 68.4%) than the enlarged coalitions that include the USA or EEC.

The three enlarged coalitions based on the {EEC, EET, CHN} coalition cover 74.0% to 83.2% of global emissions in 2010 and capture 78.7% to 81.2% of the maximum potential gain from cooperation. The USA is a member of two of these coalitions. The four enlarged coalitions based on the {USA, EET, CHN} coalition perform even better, covering 80.0% to 83.2% of 2010 global emissions and capturing 77.0% to 81.6% of the maximum potential gain from cooperation. The EEC is a member of three of these four enlarged coalitions.

Table 10. Stable Coalitions with Commitments under Shapley Value Transfer

	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW	Global net benefit
Participation	1	0	2	2	1	0	2	1	2	2	0	0	
Net benefit (billion US$)	506	1,172	1,247	226	46	457	209	193	339	175	102	451	5,121
Participation	1	0	2	0	1	2	2	1	2	2	0	0	
Net benefit (billion US$)	506	1,233	1,290	249	46	432	218	193	354	182	107	474	5,283

Participation	1	0	2	0	1	0	2	1	2	2	0	2	
Net benefit (billion US$)	506	1,234	1,291	249	46	482	218	193	354	182	107	428	5,289
Participation	1	0	0	2	1	2	2	1	2	2	0	2	
Net benefit (billion US$)	506	1,162	1,563	222	46	411	201	193	327	168	101	407	5,307
Participation	2	1	0	0	1	0	2	1	2	2	0	0	
Net benefit (billion US$)	1,005	413	1,356	204	41	394	176	163	285	147	88	388	4,659
Participation	0	1	2	2	1	0	2	1	2	2	0	0	
Net benefit (billion US$)	1,317	413	1,100	199	41	408	183	163	297	153	91	403	4,768
Participation	0	1	0	0	1	2	2	1	2	2	0	2	
Net benefit (billion US$)	1,223	413	1,307	197	41	342	166	163	270	139	85	338	4,684
Participation	2	0	1	0	1	2	2	1	2	2	0	0	
Net benefit (billion US$)	1,226	1,233	560	249	47	434	219	198	355	183	107	474	5,283
Participation	2	0	1	0	1	0	2	1	2	2	0	2	
Net benefit (billion US$)	1,227	1,234	560	249	47	482	219	198	355	183	107	430	5,289
Participation	0	0	1	2	1	2	2	1	2	2	0	2	
Net benefit (billion US$)	1,430	1,133	560	220	47	408	200	198	325	167	98	404	5,188

* '1' indicates the initial stable coalition members with commitment, '2' indicates new members subsidized by the members with commitment and '0' indicates non-members.

The best coalition includes USA, EET and CHN as initial stable coalition members and adds OOE (Other OECD countries), FSU, EEX (Energy exporting countries), IND, DAE (Dynamic Asian economies) and ROW with transfers from the net benefits due to increased cooperation. The enlarged coalition covers 82.5% of 2010 global emissions and captures 81.6% of the maximum potential gain from cooperation. It is remarkable that such a large coalition can be sustained: Only Japan, European Union and Brazil are not part of the enlarged coalition. It is an important observation that commitment by some major regions has a high potential to improve efficiency of cooperation.

The commitment analyzed in the above, however, needs careful interpretation, at least from a game-theoretic view of strategic behavior.

If some regions commit themselves to cooperate, while the remaining regions act independently and in their self-interest, it is possible to achieve a Pareto improvement if the non-members reduce their emissions in exchange for transfers from the member regions. The prospect of receiving a transfer for reducing one's emissions provided the region does not commit to cooperation, however, tends to reduce the incentive a region has to cooperate. Hoel and Schneider (1997) shows that if the disincentive effect of such possible side payments is strong, total emissions will be higher in a situation with side payments than in a situation in which the member regions commit themselves to not give transfers to free riding regions.

The strategic incentive to make a less stringent commitment with side payments may reduce the potential welfare improvement in the commitment scenario. An initial commitment by major regions, particularly most industrialized regions, however, is highly likely in the climate change negotiations. The result of the above analysis indicates that some initial commitment by major regions, such as the Kyoto Protocol, could be mobilized to expand global cooperation to combat climate change. At the same time, strategic behavior both of regions with commitments and of those without commitments should be tackled with due care to their strategic incentives.

4. Imperfect Coalitions

It is natural to define a cooperation or coalition as a state where every participant in the coalition makes a decision (emission reduction in our example) to maximize the sum of the net benefits to all of the participants in the coalition. This is, however, a strong assumption in the practical sense that it is not easy to find a mechanism to ensure such a perfect cooperative outcome in practice. It may be useful to see what happens if the assumption of perfect cooperative behavior is relaxed.

The previous analyses assumed that each participant in a coalition reduces its emission to the level at which its own marginal cost of reduction equals the sum of marginal benefits to all participants in the coalition. An imperfect coalition is defined as a coalition where each participant reduces its emissions to the level at which its own marginal cost of reduction is lower than (equal to X (<100)% of) the sum of the marginal benefits to all the participants in the coalition. We call 'X' the strength of a coalition. Then, the strength of the perfect coalition is '100'.

Table 11 shows a very interesting result: Imperfect coalitions can achieve a higher global net benefit than perfect coalitions. With CT transfers the global net benefit achieved by the perfect coalition (X=100) is US$ 2,958 for {EEC, CHN} and US$ 2,969 for {USA, CHN}. Under the imperfect coalition mechanism with X=90 the global net benefit rises to US$ 3,589 (39.5% of the maximum potential gain from cooperation) because the stable coalition is enlarged to {USA, EEC, CHN}. These three major regions are members of a stable coalition under imperfect cooperation, while the USA and EEC are not part of the same stable coalition under the perfect cooperation assumption.

As the strength of cooperation (X) decreases to 80, 70 and 60, the composition of the stable coalition does not change, but the global net benefit declines because the members make smaller emission reductions, thus decreasing the efficiency of cooperation. This pattern continues until X=50, when a new member, JPN, joins the stable coalition. The net benefit of adding a member exceeds the efficiency loss due to the lower strength of cooperation, so the global net benefit increases as X declines from 60 to 50. The same happens as again as X drops from 50 to 40 when IND or ROW joins the stable coalition producing an increase in the global net benefit.

It is interesting that imperfect cooperation is able to produce stable coalition having the United States, European Union, China and Japan, as members. None of the stable coalitions in the previous analyses included these four major regions in a single stable coalition. This indicates that it may be desirable to sacrifice the strength of the cooperation (efficiency) to achieve a desired coalition structure.

The results indicate that imperfect cooperation can increase global net benefits by enlarging the stable coalition. However, there are limits to this process. With CT transfers, global net benefits are maximized with X=90. Subsequent enlargements of the coalition yield lower global net benefits because they occur only with weaker cooperation.

Comparison of the results in Table 11 with those in Table 9 indicates that a stable coalition with a commitment is a much more effective mechanism for enlarging the stable coalition. Despite the requirement for perfect cooperation, the number of members, the global net benefits, the share of 2010 global emissions covered and the share of the maximum potential gain from cooperation captured is larger than with imperfect cooperation.

Table 11. Stable coalitions under imperfect cooperation

X	USA	JPN	EEC	OOE	EET	FSU	EEX	CHN	IND	DAE	BRA	ROW	Global Net Benefit
100	1	0	0	0	0	0	0	1	0	0	0	0	2,969
	0	0	1	0	0	0	0	1	0	0	0	0	2,958
90	1	0	1	0	0	0	0	1	0	0	0	0	3,589
80	1	0	1	0	0	0	0	1	0	0	0	0	3,450
70	1	0	1	0	0	0	0	1	0	0	0	0	3,290
60	1	0	1	0	0	0	0	1	0	0	0	0	3,103
50	1	1	1	0	0	0	0	1	0	0	0	0	3,247
40	1	1	1	0	0	0	0	1	1	0	0	0	3,289

* X indicates the strength of cooperation in a coalition structure.
** '1' indicates membership in a coalition and '0' indicates non-member.

Chapter 5. Policy Implications and Directions for Further Research

We examined climate change negotiation in a game-theoretic framework. The behavior of self-interested countries or groups of countries was analyzed with the application of global climate change simulation model, STACO, developed by Finus, Ierland and Dellink (2003). Major policy implications and future research area are discussed below.

1. Policy Implications

The results of this study reaffirm the conclusion of most of previous research: Stable coalitions to address climate change are likely to be limited to a relatively small number of large regions representing at least 30% of global emissions. Our simulation results show there is no stable coalition structure without welfare transfers. Even with welfare transfers the stable coalitions are relatively small and typically include a mix of regions with low marginal emissions abatement costs and low marginal climate change damages and regions with high marginal emissions abatements costs and high marginal climate change damages. This phenomenon stems from the free-rider incentives inherent in public good problem. The free-rider incentive becomes stronger as the size of coalition increases. The burden-sharing rule can have a significant impact on the size and composition of the stable coalitions and hence on the share of the maximum potential gains from cooperation achieved.

Trade measure could be conceived of an attractive means to deal with such free ride incentives in that the effectiveness of trade measures to deter free riders increases as the coalition size increases. That is, greater free rider incentive from larger coalition could be mitigated by a trade measure that is more effective under such a larger coalition.

We can consider two kinds of trade measures: trade controls and trade sanctions. A trade control is an instrument used in a regular way to regulate the product addressed in the treaty. A trade sanction is a specific action to coerce governmental behavior and is a response to non-compliance or non-conformity to an international norm. Trade controls have been employed in a wide array of environmental treaties including the Montreal Protocol on ozone.[31] Surveying that experience, Brack (2000) points out that similar controls for most greenhouse gases would be difficult to apply and could lead to a severe restriction on trade and an accompanying high welfare loss. Nonetheless, he argues that by the same token, such controls would be highly effective and should be contemplated as part of the evolving climate regime.[32] As far as trade sanctions are concerned, no environmental treaty employs them as an instrument of enforcement in a manner similar to WTO practice.[33] Victor (2001) contends that enforcement in the climate regime could fruitfully be linked to the WTO.[34] In general, however, research on the role of economic sanctions in international organizations does not point to a high efficacy. Although trade measures for enforcement should not be categorically ruled out, the climate regime should look for alternative enforcement techniques.[35] (Charnovitz, 2003) In spite of many complex issues, including compatibility with WTO rules, trade measures for enforcement could not be categorically ruled out. Such enforcement measures may be considered as a last resort to guarantee an effective stable agreement though not in the near future.

Imperfect cooperation can lead to a larger stable coalition that achieves a larger share of the maximum potential gains from cooperation. A committed coalition can increase its membership and

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31 In the Montreal Protocol, parties are required to ban trade with non-parties of ozone-depleting substances and products containing them.

32 More limited measures such as the application of duties or taxed against various categories of imports from non-parties could also be employed, according to Brack (2000).

33 The only two international organizations that impose trade sanctions against non-compliance are the UN Security Council and the WTO.

34 Victor (2001) suggests a program of penalty tariffs and trade sanctions to counteract the economic advantage gained through non-compliance. Stokke (2003) has also argued that trade measures could be an effective instrument against non-compliance. He predicts that such sanctions would work best if they were carried out multilaterally against the country at fault.

35 One possibility would be to enhance transparency and public participation in the international supervisory system in the hope of putting internal political pressure on governments to comply. The climate regime could also consider the use of monetary assessments against non-complying governments, a technique employed in the European Union, and being tested in new free trade agreements, e.g., U.S.-Singapore.

efficiency significantly by sharing the gains from increased cooperation with new members.

One of the most important observations of the paper is that some forms of commitments by some countries can expand the coalitions significantly and it is possible to achieve most of potential benefits. The policy implication is that strong commitments by major countries can play a vital role in establishing an effective global climate change mitigation regime.

This observation can be adapted to the principles of equity and common but differentiated responsibilities under the UNFCCC. The Convention requires the industrialized countries to take the lead in modifying longer-term trends in emissions. The industrialized countries also have a special obligation to provide new and additional financial resources to developing countries to help them tackle climate change, as well as to facilitate the transfer of climate-friendly technologies to both developing countries and countries with economies in transition. These principles provide a useful framework to facilitate wider participation. Though the results of our simulation propose a leading role for major countries, including some developing countries, it also shows the necessity for compensation to the leading developing countries via adequate transfer mechanisms.

The clean development mechanism (CDM), which saves cost of reductions and does not decrease global emission itself, is a useful mechanism to be continued. It is necessary, however, to devise a new mechanism to mobilize transfer from major countries with initial commitments to induce other countries to make additional reductions in a global sense, not just a reduction moving from one country to another as in the CDM.

We can conceive of a financial mechanism playing a role to enlarge an initial coalition, we call it Mitigation Fund, under which the countries with commitments contribute financial or other kind of resources and utilize the resources to subsidize additional emission reductions anywhere in the world.[36] Mitigation Fund can subsidize

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[36] The additionality in Mitigation Fund is different from that in the CDM. The additionality in the CDM requires that emissions reduction should be additional to what would have occurred in the developing countries and any additional reduction gives credits to investor countries who then can use it to increase their own emissions. The additionality in Mitigation Fund requires that emissions reduction should be additional

any additional emissions reduction, wherever it is occurred, and therefore resource transfer can be made to buy back, and not to resell as in the CDM, emission reductions from countries without commitments or emission allowances from countries with commitments.

An agreement on contributions by individual countries is required in order to set up Mitigation Fund. Such an agreement on burden sharing formula may be a quite difficult task for international society, but it might be possible if we extend our former experience under United Nations scale of assessment for budget allocation. Mitigation Fund can play a supplementary role to reduction commitment particularly if a single policy instrument, such as Kyoto commitment, is not sufficient to solve the global mitigation problem. If emissions reduction commitments under an international environmental agreement are not strong enough to achieve the first-best global reduction target, Mitigation fund could be utilized to fill the gap by way of subsidizing additional emission reductions.

Stable coalitions under imperfect cooperation indicate the need to balance the strength of cooperation and the scope of coalition. Reduction obligations that are too strong may not be desirable from the global perspective if it deters wider participation.

China is found to be an essential member of virtually every stable coalition. China can contribute more to the welfare gains from forming a coalition than any other region. An equitable transfer mechanism needs to be devised and applied in future negotiations to induce participation by China.

2. Directions for Further Research

This study examined a single-period game with complete information. The real world situation is a repeated multi-period game with incomplete information (information asymmetry and uncertainty).

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and do not allow any credits for them that can be used to increase emissions in other place.

A simple first step is to analyze the sensitivity of the stability of coalitions over a reasonable range of benefit and cost parameters to take into consideration the high uncertainties inherent in the climate change science and the evolution of mitigation technologies. Such analyses could be limited to the most promising transfer rules – Shapley value and grandfathering. Alternatively, the anlysis could seek to find which burden sharing rule induces the widest stable coalition.

Secondly, the decision-making framework under uncertainty needs to be incorporated to consider the risk-related behavior of players. Possible further research with uncertainty and information asymmetry includes:

- Stable coalitions with perfect cooperation under Shapley and grandfathering transfer rules
- Stable coalitions with perfect cooperation as committed coalitions under Shapley and grandfathering transfer rules
- Stable coalitions with imperfect cooperation under Shapley and grandfathering transfer rules
- Stable coalitions with imperfect cooperation as committed coalitions under Shapley and grandfathering transfer rules
- Analysis of a cooperation mechanism under which the strength of cooperation increases as the size of the coalition grows to see if such a rule contributes to broadening the stable coalition
- A comparison of the efficiency of strategies that allow multiple coalitions with strategies (imperfect cooperation, committed coalitions) to increase the size of a single coalition.

Thirdly, further research on welfare transfer mechanisms in some of the above contexts is warranted and could include:

- The effectiveness of ‘hot air’ as a welfare transfer mechanism
- The effectiveness of different forms of emissions limitation commitments, such as absolute caps, intensity targets, non-binding caps, dual intensity targets, and others as a welfare transfer mechanism

- The role of the Kyoto mechanisms as a welfare transfer mechanism
- The effectiveness of Funds established by the Convention and Protocol as a welfare transfer mechanism
- The effectiveness of trade measures as a means of increasing the stability of coalitions (by increasing the benefits to members and reducing the free rider benefits to non-members)
- The effectiveness of cooperation on research and development and technology transfer as welfare transfer mechanisms.

Fourth, procedures for establishing and maintaining coalitions in multi-period repeated games warrant further research. Possible approaches include the MDP procedure by Malinvaud (1971) and Dreze and Poisson (1971) and the "tradable tagged permit system" proposed by Ahn and Kim (2001).[37]

Finally, it would be useful to investigate the effectiveness of other provisions as means of helping to form and maintain stable coalitions, including minimum participation rules, exclusivity. A minimum participation rule is an important option for climate change negotiations. Carraro, Marchiori and Oreffice (2003) indicates that a minimum participation rule is generally helpful to enhance the environmental effectiveness of an international agreement, in particular when the number of negotiating countries is not too large. A minimum participation rule requiring most or all of regions to ratify before an agreement enters into force can be an effective mechanism as well.

[37] Ahn and Kim (2001) proposes a tradable permit system, called "tradable tagged permit system", which is specifically geared to global environmental issues of long-term dynamics. This is an extended emission permit system composed of various types of permits, one for each country or class of countries. It induces countries to reveal their damages, in addition to the costs, through their permit prices. It is shown that this achieves a Pareto-superior outcome than without the system, and that the repeated application of this scheme converges to the global first-best steady state. A numerical analysis with empirical data shows that the scheme achieves most of the potential gains from global cooperation, even with an initial allocation scheme based on voluntary pledge levels that gives participation incentives for all countries. If it is not possible to reach an efficient agreement on climate change at the initial stage, we can improve the outcome with this kind of inter-temporal improvement mechanism.

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APPENDIX. Explanation on Empirical Model (STACO)

1. Introduction

Detailed explanation on STACO(STAbility of COalitions) model by Finus, Ierland and Dellink (2003) is provided in this appendix. Calibration in the model is based on DICE-model by Nordhaus (1994). There are twelve world regions in the model. STACO relies on damage cost estimates of Fankhauser (1995) and Tol (1997) and abatement cost estimates of Ellerman/Decaux (1998).

2. Emissions and Concentration

STACO focuses on carbon dioxide, but the exogenous level of other greenhouse gases is included in the calibration of the damage cost function (Nordhaus 1994). For the development of emissions and the stock of carbon dioxide in the business-as-usual-scenario (BAU), calibration is based on the market scenario in DICE. This scenario assumes no emission reduction, though there is a feedback between the environment and the economy. In DICE, global emissions grow non-constantly over time. However, it turns out that a linear specification of uncontrolled global emissions (e_t) provides a good fit for the development of the stock of carbon dioxide:

$$e_{t+1} = e_t + d_E \quad \text{..} [2]$$

where d_E denotes the uncontrolled annual growth of global emissions, $e_t = \sum_{i=1}^{N} e_{it}$. N is the number of regions and to N=12 in the model.

STACO starts in 2010 and covers a period of 100 years in order to capture the long-run effects of the global warming problem. Thus, with reference to equation [1], t=2011, ..., T=2110. For emissions in 2010, STACO chooses the value of DICE, which amounts to 11.96 giga tons CO_2. OLS-regression gives d_E = 0.153. The stock of carbon dioxide in the atmosphere at time t is expressed in the standard way by the following equation:

$$M_t\left(q_{2011},\mathrm{K},q_t\right)=M_{pre\text{-}ind}+(1-\delta)^{(t-2010)}\cdot\left(M_{2010}-M_{pre\text{-}ind}\right)+\sum_{s=2011}^{t}\left((1-\delta)^{t-s}\cdot\omega\cdot(e_S-q_s)\right)\text{[3]}$$

where $q_t = \sum_{i=1}^{N} q_{it}$.

The airborne fraction of total net emissions (BAU-emissions minus abatement) that remains in the atmosphere is assumed to be 64 percent (ω=0.64) according to DICE, which decays with rate δ =0.00866 per annum. In the BAU- scenario with no abatement, the uncontrolled stock according to [3] in 2110 is 1,585 giga tons whereas the corresponding value taken from DICE is 1,576 giga tons. Denoting the uncontrolled stock at time *t* by $M_t(0)$, then [3] can be rewritten:

$$M_t\left(q_{2011},\mathrm{K},q_t\right)=M_t(0)-\sum_{s=2011}^{t}(1-\delta)^{t-s}\cdot\omega\cdot q_S \quad \dots\dots\dots\dots\dots \text{[4]}$$

which simplifies if we assume q_{it} (and hence also) constant over time. For the stock of CO_2 in 2110 this leads to:

$$M_{2110}(q)=M_{2110}(0)-\left[\sum_{t=2011}^{2110}(1-\delta)^{2110-t}\cdot\omega\right]\cdot\frac{q}{100} \qquad \dots\dots\dots \text{[5]}$$

where $q=\sum_{t=2011}^{2110} q_t$, the term in brackets is a constant equal to 42.9 and $M_{2110}(0)=1585$ giga tons.

3. Global Damage Cost Function

In DICE global damages depend on world temperature increase, ΔT_t, global GDP, Y_t, and parameter γ_D that measures the impact on GDP due to an increase in temperature of 3 degrees Celsius compared to the pre-industrial level.

$$D_t=\gamma_D\cdot\left[\frac{\Delta T_t}{3}\right]^2\cdot Y_t \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{[6]}$$

In order to establish a direct link between concentration and damages, STACO follows Germain and Van Steenberghe (2001), who use the following approximation of the full climate module:

$$\Delta T_t = \eta \cdot \ln\left(\frac{M_t}{M_{pre-ind}}\right) \qquad [7]$$

where η is a parameter. Substituting [7] into [6], gives:

$$D_t = \left(\frac{\gamma_D}{9}\right) \cdot \left[\eta \cdot \ln\left(\frac{M_t}{M_{pre-ind}}\right)\right]^2 \cdot Y_t \qquad [8]$$

In DICE, it is assumed that a doubling of the carbon dioxide concentration ($2 \cdot M_{pre-ind}$) leads to an increase in temperature of 3 degrees.[1] Thus from [7], $\eta = 3/\ln(2)$, and γ_D can be interpreted as damages in percentages of GDP for a doubling of concentration:

$$D_t = \left[\frac{1}{\ln(2)} \cdot \ln\left(\frac{M_t}{M_{pre-ind}}\right)\right]^2 \cdot (\gamma_D \cdot Y_t) \qquad [9]$$

Though this damage function is non-linear, it can be approximated by a linear function in the relevant range of the study, that is, between the stock in 2010 (1.4 times pre-industrial level) and the estimated uncontrolled level in 2110 (3.5 times pre-industrial level):

$$D_t = \left[\gamma_1 + \gamma_2 \cdot \left(\frac{M_t}{M_{pre-ind}}\right)\right] \cdot (\gamma_D \cdot Y_t) \qquad [10]$$

where γ_1 and γ_2 are calculated via OLS-regression. Further manipulation that considers the fact that (i) a doubling of concentration occurs between 2055 and 2065 in DICE and also in the above approximation, (ii) the undiscounted GDP in this period is 70,284 billion US$ and (iii) $M_{pre-ind}$ =590 giga tons CO_2, gives[2]:

$$D_t = \gamma_D \cdot (\varphi_1 + \varphi_2 \cdot M_t) \qquad [11]$$

where $\varphi_1 = \gamma_1 \cdot Y_{2061} = -140146$ billion US$ and $\varphi_2 = \gamma_2 \cdot (1/M_{pre-ind}) \cdot Y_{2061} = 178.331$ billion US$ per Gton.

1 This is based on an exogenous additional impact of other greenhouse gases on radiative forcing.

2 All market values are expressed in billion US$ of 1985. This applies to damages, benefits and abatement costs.

4. Global and Regional Benefit Functions

Due to the assumption of stationary abatement strategies, we can express benefits in year t as a function of total abatement over the entire period, $q = \sum_{t=2011}^{2110} q_t$. Noting that [11] reads $D_t(M_t(q)) = \gamma_D \cdot (\varphi_1 + \varphi_2 \cdot M_t(q))$ if abatement is explicitly accounted for, benefits from global abatement in year t, $B_t(q)$ is derived as follows:

$$\begin{aligned} B_t(q) &= D_t(M(0)) - D_t(M_t(q)) \\ &= \gamma_D \cdot [\varphi_1 + \varphi_2 \cdot M_t(0)] - \gamma_D \cdot [\varphi_1 + \varphi_2 \cdot M_t(q)] \quad \ldots\ldots\ldots\ldots [12] \\ &= \gamma_D \cdot \varphi_2 \cdot (M_t(0) - M_t(q)) \end{aligned}$$

Summing over all periods, discounting benefits with a discount rate of 2 percent, inserting φ_2 =178.331 from above gives total benefits $TB(q)=\gamma_D \cdot 1385.1 \cdot q$ and marginal total benefits $MTB(q)=\gamma_D \cdot 1385$. STACO uses the recent estimate of Tol (1997) who estimates damage costs of 2.7 percent of GDP for a doubling of concentration and hence γ_D =0.027. This leads to $TB(q)= 37.40 \cdot q$, implying discounted marginal global benefits of 37.40 US$ per ton CO_2 $(MTB(q) = 37.4)$.

STACO allocates global benefits from reduced environmental damages to the various world regions based on the assumption that $TB_i(q) = s_i \cdot TB(q)$ (and hence $MTB_i(q) = s_i \cdot MTB(q)$) where s_i is the share of region *i*.

There are 12 regions: USA (USA), Japan (JPN), European Union (EEC), other OECD countries (OOE), Eastern European countries (EET), former Soviet Union (FSU), energy exporting countries (EEX), China (CHN), India (IND), dynamic Asian economies (DAE), Brazil (BRA) and "rest of the world" (ROW).[3] The share of global benefits (s_i) is mainly based on Fankhauser(1995)´s estimates.

[3] EEC comprises the 15 countries of the European Union as of 1995. Other OECD countries (OOE) includes among other countries Canada, Australia and New Zealand. Eastern European countries (EET) includes for instance Hungary, Poland, and Czech Republic. Energy Exporting Countries (EEX) includes for example the Middle East Countries, Mexico, Venezuela and Indonesia. Dynamic Asian economies (DAE) comprises South Korea, Philippines, Thailand and Singapore. Rest of the World (ROW) includes for instance South Africa, Morocco and many countries in Latin America and Asia. For details, see Babiker et al. (2001).

5. Derivation of Abatement Cost Functions

For the specification of the abatement cost function, STACO rely on estimates of the EPPA model that are reported in Ellerman and Decaux (1998). They assume an annual abatement cost function of the following form:

$$AC_{it}(q_{it}) = \tfrac{1}{3} \cdot \alpha_i \cdot (q_{it})^3 + \tfrac{1}{2} \cdot \beta_i \cdot (q_{it})^2 \qquad \text{.......................} [13]$$

In order to derive total abatement costs of region *i*, $TAC_i(q_i)$, we sum [13] over t=2011,...,2110 and discount with discount rate r, $TAC_i(q_i) = \sum_{t=2011}^{2110} (1+r)^{-(t-2010)} AC_{it}(q_i)$.

Noting that because of stationary strategies, we can write $TAC_i(q_i) = AC_{it}(q_i) \cdot \sum_{t=2011}^{2110} (1+r)^{-(t-2010)}$ and discounting abatement costs with the same uniform discount rate of 2 percent as in the case of benefits, we get $TAC_i(q_i) = 43.1 \cdot AC_{it}(q_i)$ and marginal total abatement costs of $MTAC_i(q_i) = 43.1 \cdot MAC_{it}(q_i)$.

The payoff function is defined as follows:

$$\pi_i = TB_i(q) - TAC_i(q_i) \qquad \text{..} [14]$$

In equilibrium, $\sum_{i \in c^i} MTB_i(q) = MTAC_i(q_i)$

한글 요약[1]
(Summary in Korean)

본 연구는 기후변화협상 문제를 게임이론적 모형으로 정식화하고, 다양한 협력 시나리오 하에서의 균형을 분석함으로써 국제협상의 효율을 높이기 위한 정책적 시사점을 도출하였다.

국가간의 게임을 안정적(stable)인 연합체(coalition) 구성의 관점에서 2단계 게임으로 정식화하였다. 1단계에서 각 국가는 연합체에 참여할 것인가를 (동시에) 결정하고, 2단계에서는 국가별로 기후변화 대응노력(온실가스 감축량)을 (동시에) 결정한다. 2단계에서는 연합체에 속한 국가들은 연합체 전체의 이익을 최대화하는 수준으로 감축량을 결정하며, 연합체에 포함되지 않은 국가들은 개별적으로 자국의 이익을 최대화 하는 수준으로 감축량을 결정한다. 이러한 게임의 균형 개념으로 안정적 연합체(stable coalition)를 정의하였다. 안정성(stability)을 만족하기 위해서는 내적 안정성과 외적 안정성을 동시에 만족하여야 하며, 내적 안정성(internal stability)은 연합체에 속한 모든 국가가 탈퇴하지 않고 남아있을 유인이 있을 때 만족되며, 외적 안정성(external stability)은 연합체 밖의 모든 국가가 연합체에 가입할 유인이 없을 때 달성된다.

시뮬레이션 분석을 위해서는 Finus, Ierland와 Dellink (2003)가 개발한 STACO라는 모델을 적용하였다. STACO 모형은 기후변화로 인한 피해와 기후변화 대응비용(온실가스 감축비용) 모두를 포함하고 있고, 기후변화 문제의 주요 협상 주도국들을 모두 포함하고 있어 본 연구의 목적에 적합한 것으로 평가되었다. 특히 12개나 되는 세분화된 지역구분을 하고 있어 다수 국가가 존재할 경우에 심각성이 더해지는 무임승차 문제를 분석하기에 매우 적절한 모형으로 선택되었다.

시뮬레이션 분석결과, 다른 선행연구에서와 같이 안정적인 연합체가 구성되기란 매우 어렵다는 점이 확인되었다. 연합체를 구성하는 국가들 간에 후생 이전(welfare transfer)이 없는 경우 2개 이상의 국가 혹은 국가군으로 만들어지는 어떤 연합체도 안정성을 만족하지 못했다.

[1] 본 보고서가 영문으로 작성된 점을 고려하여 영문요약(abstract)과 다르게 한글 요약은 보다 상세한 설명을 포함하도록 작성되었다.

국가(군)간에 후생 이전을 허용할 경우에도 비록 안정적인 연합체가 형성될 수 있으나, 그 규모는 매우 작은 것으로 나타났다. 이 경우 형성되는 연합체의 구조적 특징 중 하나는 온실가스 저감 한계비용이 낮고 기후변화에 따른 피해의 한계비용도 낮은 국가(군)와 함께 반대의 특성을 갖는 국가(군), 즉 저감 한계비용과 피해 한계비용이 모두 높은 국가(군)를 동시에 포함한다는 것이다. 이는 상호 연합에 따른 시너지 효과가 커지는 이러한 국가(군)의 연합이 서로간의 후생 이전을 통해 안정적으로 유지될 수 있다는 점을 의미한다.

보다 구체적으로, 후생이전의 형태로 두 가지가 고려되었다. 하나는 Chander와 Tulkens (1995, 1997)가 제안한 후생배분방식으로서 연합체의 구성에 따른 추가적 이익을 기후변화의 한계 피해비용에 비례하여 나누어 갖는 방식(이하 CT 방식)이다. 다른 하나는 협조적 게임이론에서 균형의 개념으로 적용되고 있는 샤플리 값(Shapley value)에 따른 배분방식이다.[2] CT 방식 하에서는 {미국, 중국}과 {EU, 중국}의 두개의 안정적 연합체가 발견되었다. 지구 전체의 연합체 형성이 가능할 때 성취가능한 최대 후생에서 아무런 연합도 형성되지 않았을 때의 후생을 뺀 값은 성취가능한 후생 증가분이라 정의할 때, CT 방식 하에서는 이의 약 1/4 수준을 달성할 수 있는 것으로 분석되었다. 발견된 두 가지 경우 모두 중국을 포함하고 있으며, 미국 또는 EU에서 중국으로의 후생이전이 가능함에 따라 중국이 연합체에 참여할 유인을 갖게 된다. 샤플리 값을 적용할 경우 안정적 연합체는 {미국, 동구권, 중국}, {일본, 동구권, 중국}, {EU, 동구권, 중국}의 세가지 경우가 발견된다. 동구권의 참여가 특징적이나 이로 인한 후생 증가분은 크지 않았다. 하지만 게임이론에서 정치적 영향력을 합리적으로 표현하는 개념으로 많이 적용되고 있는 샤플리 값이 보다 큰 연합체 형성에 기여한다는 점은 의미가 있다고 판단된다.

후생이전에만 의존하는 방법으로는 광범위한 연합의 형성이 어렵고 이는 지구환경문제의 해결을 어렵게 한다. Carraro와 Siniscalco (1993)가 제시한 바 있듯이 일부 국가의 연합체 형성 이후에 새롭게 연합체에 참여하는 국가(군)에 대해 기존 연합체 구성원이 추가적인 후생 증가분을 이전함으로써 연합체를 확대할 수 있는가에 대하여 분석하였다(stable coalitions with commitments). 이 경우에도 CT 방식과 샤플리

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2 협조적 게임이론에서 활용되는 이익배분방식 중 Nucleolus의 개념과 내쉬협상 해(Nash Bargaining Solution)도 검토되었으나 전자는 계산상의 복잡성으로 적용되지 못하였고 후자는 분석결과 의미 있는 (2개 이상의 국가(군)를 포함하는) 안정적 연합체를 형성하지 못하는 것으로 나타나 설명에서 제외되었다. 또한 연합체의 구성원별로 연합체 형성에 따른 추가적인 기여분에 비례하는 이익배분방식도 검토하였으나 의미 있는 안정적 연합체를 형성하지 못하는 것으로 분석되었다.

방식을 적용하였으며, 1차적으로 연합체를 형성하는 경우는 앞에서 (신규 참여자에 대해 기존 연합체가 추가적인 후생이전을 하지 않는 경우) 안정적 연합체로 발견된 경우로 한정하였다. (CT 방식의 경우 2개의 지역으로 구성된 두 가지의 연합체이며, 샤플리 방식의 경우 3가지 연합체가 가능함) 이처럼 신규 참여자를 지원할 경우 안정적 연합체의 규모는 크게 확대되었다. CT 방식의 경우 4개의 지역으로 구성되는 4개의 안정적 연합체가 발견되었으며, 샤플리 방식의 경우는 7개에서 9개의 지역이 참여하는 안정적 연합체 10개가 발견되었다. 이 중 가장 높은 후생을 성취하는 연합체는 미국, 동구권 및 중국이 1차 연합체를 형성하고 기타 OECD 국가, 구소련, 에너지수출국, 인도, 아시아 선발개도국 및 기타 지역을 신규 참여자로 지원하는 경우이다. 이러한 연합체는 전체계 배출량(2010년 기준)의 82.5%를 차지하며, 가능한 후생 증가분의 81.6%를 성취하는 것으로 평가되었다.

게임이론적 측면에서 일부 국가의 1단계 의무부담(commitment)이 2단계에서 신규 참여자를 지원할 경우, 1단계에서의 의무부담 자체가 약화될 것이란 점을 주의해야 할 것이다. 하지만 개도국에 앞서 주요 선진국이 1차적으로 의무부담에 선도적 역할을 해야 하고, 또한 그러한 경향이 다수의 국제환경협상에서 발견된다는 점에서, 주요 국가의 1차적 의무부담과 이를 토대로 국제적인 후생이전을 통해 협력구조를 확대·강화해 나가는 것은 매우 중요한 정책적 방향이라 평가된다. 또한 분석결과 안정적 연합체로 평가된 모든 경우에 중국은 구성원으로 참여하는 것으로 나타났다. 즉, 중국이 포함되지 않는 연합구조는 안정적이지 못하게 나타났다. 이는 대규모의 저비용 감축잠재량을 갖고 있는 중국이 참여하지 않는 연합구조는 안정성을 확보할 만큼 충분한 잉여 후생을 창출하지 못함을 의미하는 것으로 해석된다. 개도국 중에서도 중국과 같이 온실가스 감축여력이 높은 국가의 경우 비록 기후변화 피해비용이 낮다 하더라고 가능한 한 1차적인 감축의무 부담에 선도적인 역할을 할 필요가 있으며, 이러한 국가에 대해서는 적절한 후생이전 메커니즘을 통해 참여 유인을 제공하여야 할 것이다.

마지막으로 연합체를 구성하는 국가(군)간의 협동구조 자체의 강도에 대한 분석을 시도하였다. 가령 교토의정서상의 부속서 I 국가 그룹이나 혹은 오슬로의정서의 경우 유럽연합과 같이 의무부담 측면에서 연합구조를 형성하는 경우가 있지만, 현실적으로 그룹 전체의 이익을 극대화하는 수준으로 강도 높은 감축의무가 공유될 것이라고 예측하는 데에는 한계가 있기 때문이다. 따라서 연합체 내부의 의사결정이 최적의 수준으

로 이루어지지 않을 경우, 안정적 연합체의 형성이 어떤 영향을 받는지를 분석하였다. 연합체 단위의 의무부담 강도가 최적 수준보다 낮게 될 경우, 일정한 수준까지는 의무부담 강도의 약화가 오히려 연합체의 확대를 가져옴으로써 지구전체의 후생을 증가시킬 수 있음이 확인되었다. 안정적 연합체의 형성을 통해 지구적 후생을 극대화하기 위해서는 연합체 소속국가(군)의 의무부담 수준을 너무 강하지 않은 수준(연합체 전체의 후생극대화 수준보다 낮은 수준)으로 유지함으로써 의무부담 강도와 참여국가의 확대 사이에 균형 있는 고려가 필요하다. 하지만 다수의 경험적 연구결과를 볼 때, 다수의 국제환경협상에서 생성되는 연합체의 의무부담강도는 상호협력이 없는 개별적인 노력의 수준보다 크게 향상되지 않을 수 있다는 점도 간과되어서는 안될 것이다.