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An Empirical Assessment of Measures to Enhance the Success of Global Climate Treaties*

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An Empirical Assessment of Measures to Enhance the Success of Global Climate Treaties*

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Abstract

We analyze important forces that hamper the formation of successful self-enforcing agreements to mitigate global warming. The analysis combines two modules: a) a computable general equilibrium model that captures the feedback between the economy, environmental damages and the climate system and b) a game theoretic model that determines stable coalitions in the presence of free-riding incentives. We consider two types of measures to enhance the success of international environmental treaty-making: a) transfers, aiming at balancing asymmetric gains from cooperation; b) institutional changes, aiming at making it more difficult to upset stability of a treaty. We find that institutional changes may be as important as transfers and should therefore receive more attention in future international negotiations.

JEL-Classification: C68, C72, H41, Q25

Keywords: design of climate treaty protocol, coalition formation, non-cooperative game theory, integrated assessment model

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1. Introduction

The voluntary provision of public goods is a well-known problem in economics (Bergstrom/Blume/Varian 1986 and Cornes/Sandler 1996). Non-excludability from positive externalities leads to the underprovision by private entities. In the national context, governments can mitigate this problem. They can provide the appropriate level of public goods with financial resources from taxation. However, in the international context, this is more difficult because no "world government" exists that can take up this role. Consequently, international treaties have to rely on voluntary participation and must be designed in a self-enforcing way. In the presence of free-rider incentives, this frequently means that not all countries benefiting from an international public good participate and/or the level of provision only marginally exceeds non-cooperative levels (Murdoch/Sandler 1997a, b). The mitigation of global warming exemplifies this problem. In 1997, the Kyoto Protocol was signed after more than ten years of difficult negotiations. This treaty aims at reducing global greenhouse gas emissions by 5.2 percent compared to 1990 levels by 2008-12 – far below what would be advisable according to cost-benefit analyses.[1] Today, 7 years later, the Kyoto Protocol has still not been ratified and hence has not come into force. Even worse, the USA declared in 2001 that they withdraw from the Protocol. In the aftermaths of this decision, also other signatories started demanding to reduce their previously accepted moderate abatement targets even further.

From the bumpy road towards an international climate agreement it is evident that there are some fundamental characteristics associated with the climate change that makes this environmental problem even more difficult to solve than other transboundary pollution problems. Therefore, this paper has two purposes: a) shedding light on some fundamental forces that hamper successful treaty-making in the context of greenhouse gas mitigation and b) considering measures to improve the success of self-enforcing climate treaties. Our analysis combines two modules: a) a computable general equilibrium model that captures the feedback between the economy, environmental damages and the climate system and b) a game theoretic model that determines stable coalitions in the presence of free-riding incentives. The combination of rigorous game theoretic analysis and numerical simulations constitutes a novelty compared to the existing literature on international environmental agreements.

We identify four major forces that constitute obstacles for successful international environmental agreements (IEAs) that are particularly pronounced in the case of climate change miti-

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[1] For instance, see Nordhaus/Boyer (2003) and Kolstad/Toman (2001) for an overview of cost-benefit studies on climate change.

gation. *First*, the larger the number of agents involved in the provision of public goods, the larger free-rider incentives will be (Cornes/Sandler 1996). Greenhouse gases emissions disperse *uniformly* in the atmosphere and therefore constitute a *pure public* bad by which *all* nations are affected. In contrast, environmental problems, like for instance the “acid rain” in Europe (regulated under the 1985 Helsinki and 1994 Oslo Protocol) or transboundary water pollution in river basins (Rhine 2020 Action Plan of the International Commission for the Protection of the Rhine adopted in 1998) are of a more regional nature and therefore cooperation proves somewhat easier.

Second, long-run effects make cooperation more difficult than short and mid term effects. Greenhouse gas emissions accumulate in the atmosphere and decay only at a very low natural rate. Thus, current measures can steer atmospheric concentrations only in the very long-run (IPCC 2001). Consequently, abatement costs are to be borne today, but benefits in the form of reduced damages will only materialize in the far future. Since it takes more than a century before the benefits of emission reduction programs become visible, it is evident that even with a low discount rate, today’s abatement measures are characterized by very low benefit-cost ratios. Hence, ambitious emission reduction programs are not to be expected, which is even more true considering that short term success is important for governments. In contrast, sulfur emissions, which cause acid rain, also have a time-dimension, but benefits of abatement measures become visible after 5 to 10 years already.

Third, high abatement costs and uncertain damages make cooperation unattractive. Many climate studies come to the conclusion that abatement costs are likely to be high for severe emission cutbacks (Weyant 1999). Moreover, damages are difficult to estimate and are uncertain because of the complexity of the climate system (IPCC 2001). In contrast, abatement costs of sulfur emissions constantly dropped in the 80 and 90´s, damages were visible in the form of “forest death”, corrosion of ancient buildings and the decline of fish stocks in lakes that could be better estimated (Burtraw et al. 1997). Thus, even countries that did not sign the Helsinki Protocol on sulfur reduction in 1985 reduced their emissions substantially and most members reduced their emissions much beyond agreed targets (Finus/Tjøtta 2003 and Murdoch/Sandler 1997a).

Fourth, as a tendency, the larger the asymmetry in terms of the cost-benefit structure from abatement, the larger the asymmetry will be in terms of the gains from cooperation, posing problems to self-enforcing treaties (Finus 2002). Given the global nature of greenhouse gases, the cost-benefit structure is very uneven between countries because of the large differences between industrialized countries, economies in transition and developing countries. Clearly, also the Helsinki Protocol involved different actors, but all belonged to the “European continent”.

In order to overcome these difficulties, we suggest two ways to alleviate problems. Clearly, we cannot change the nature of an environmental problem, but we may consider different designs of environmental treaties. One obvious measure in the presence of asymmetries between players is transfers that may help to implement at least second-best solutions. We consider various transfer schemes that have been proposed in the literature and study their effect on treaty formation.

Another measure is a change of institutional rules where we focus on membership rules. At first glance, this may seem a less obvious measure since in the face of positive externalities from abatement, no restriction on membership seems necessary or advisable. However, as we show, changing the rule of open membership, which is typical for public goods, to exclusive membership, which is typical for club goods, can have a significant impact for successful treaty making.

In what follows, we describe the empirical model in section 2 and discuss fundamental features of coalition formation in section 3. Subsequently, we analyze stability and measures to improve upon the success of climate change treaties in section 4. Section 5 raps up and points to future research questions.

2. Empirical Model

The CLIMNEG World Simulation Model (in the sequel referred to as CWSM) is an integrated assessment, economy-climate model that resembles closely the seminal RICE model by Nordhaus/Yang (1996). An overview of the equations and parameters of the model are provided in the Appendix. A more detailed exposition of the model can be found in Eyckmans/Tulkens (2003). An important feature of integrated assessment models is the endogenous feedback of climate change damages on production and consumption possibilities. The economic part of CWSM consists of a longterm dynamic, perfect foresight Ramsey type of optimal growth model with endogenous investment and carbon emission reduction decisions. The carbon cycle and temperature change module are the same as in RICE.

In the CWSM, the world is divided into six regions: *USA*, *JPN* (Japan), *EU* (European Union), *CHN* (China), *FSU* (Former Soviet Union) and *ROW* (Rest of the World). In each region i, and in every time period t, t={1990, 2000, ..., 2330}, the following budget equation describes how “potential GDP”, $Y_{i,t}$, can be allocated to consumption, $Z_{i,t}$, investment, $I_{i,t}$, emission abatement costs, $Y_{i,t}C_i(\mu_{i,t})$, and climate change damages, $Y_{i,t}D_i(\Delta T_t)$:

$$Y_{i,t} = Z_{i,t} + I_{i,t} + Y_{i,t}\, C_i\left(\mu_{i,t}\right) + Y_{i,t}\, D_i\left(\Delta T_t\right) \tag{1}$$

Output is produced with a production function F that maps combinations of capital stock $K_{i,t}$ and labour input $L_{i,t}$ into regional output. The production technology is assumed to satisfy constant returns to scale of the Cobb-Douglas type:

$$Y_{i,t} = a_{i,t} F\left(K_{i,t}, L_{i,t}\right) \equiv F_{i,t}\left(K_{i,t}\right) \tag{2}$$

where $a_{i,t}$ is a technology shift parameter that is assumed to increase exogenously over time[2]. Since labour supply is assumed to be inelastic and exogenous, we can relate output only to capital, incorporating the technology parameter $a_{i,t}$ in the "new" production function $F_{i,t}(K_{i,t})$. From the input data reported in the Appendix, it is evident that capital at t=1990 is mainly concentrated in USA, JPN and EU whereas the labor force is concentrated in CHN and ROW.

Capital accumulation is described in the standard way:

$$K_{i,t+1} = \left[1 - \delta_K\right] K_{i,t} + I_{i,t} \tag{3}$$

where δ_K denotes the capital depreciation rate.

The cost function C_i maps abatement effort $\mu_{i,t}$ into the share of “potential GDP” devoted to abatement. In order to obtain abatement costs, C_i has to be multiplied by $Y_{i,t}$ as this is done in expression (1). Abatement costs are assumed to be an increasing and convex function of emission abatement effort. Abatement effort $\mu_{i,t} \in [0,1]$ measures the relative emission reduction compared to the Business-as-usual scenario (BAU) without any abatement policy. For the parameters given in the Appendix, USA, JPN and EU face steep and CHN and ROW flat marginal abatement costs measured in US$ per ton of carbon. The regional differences in abatement costs reflect mainly differences in energy efficiency. Energy efficient regions often face higher costs to cut back emissions than regions characterized by low energy efficiency.

The damage function D_i maps temperature change ΔT_t into the share of “potential GDP” destroyed by climate change damages. Hence, damage costs are computed by multiplying D_i

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[2] The rate of technological progress differs between regions and decreases exogenously over time. The time paths of the rates of technological progress are taken from Nordhaus/Yang (1996).

by $Y_{i,t}$. Climate change damages are an increasing and convex function of temperature change ΔT_t. From the input data in the Appendix, it is evident that damage functions are particularly steep in EU and ROW, to a lesser extent in USA, JPN, and relatively flat in FSU and CHN. The high damage estimate (as a percentage of "potential GDP") for ROW is due to the fact that climate change is believed to affect developing countries more strongly than industrialized countries because their economies tend to depend more on climate related production processes like agriculture, fishery and forestry (IPCC 2001). The low damage estimate for FSU is due to some expected benefits from moderate temperature increase like the expansion of arable land to the north.

Temperature change ΔT_t is related to carbon concentration according to an increasing function G (see Appendix for details):

$$\Delta T_t = G(M_t) \tag{4}$$

where concentration in turn depends on emissions that accumulate in the atmosphere according to a standard linear stock externality process:

$$M_{t+1} = [1-\delta_M]M_t + \beta \sum_{i \in N} E_{i,t} \tag{5}$$

where M denotes carbon concentration, δ_M the natural decay rate and β the airborn fraction of emissions, that is, the fraction of emissions added to atmospheric concentrations. Since $\beta = 0.64$, almost 2/3 of carbon emissions are added to the carbon stock which decrease very slowly since $\delta_M = 0.0833$.

Emissions are proportional to "potential GDP":

$$E_{i,t} = \alpha_{i,t}\left[1-\mu_{i,t}\right]Y_{i,t} \tag{6}$$

where the exogenous parameter $\alpha_{i,t}$ denotes the emission-ouput ratio and is assumed to decline over time due to exogenous energy efficiency improvements[3].

Taken together, we call $Y_{i,t}$ on the left hand side of equation (1) as "potential GDP" because this is the output that could be produced in the absence of the climate change problem. Rewriting (1) allows us interpreting the lefthand side of the budget equation as "green GDP", that is, production net of climate change damages and abatement costs:

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[3] Also the time paths of exogenous energy efficiency improvements for the different regions are taken from Nordhaus and Yang (1996).

$$Y_{i,t}\left[1-C_i\left(\mu_{i,t}\right)-D_i\left(\Delta T_t\right)\right]=Z_{i,t}+I_{i,t} \tag{7}$$

We measure welfare of a country as total lifetime discounted consumption:

$$w_i(s)=\sum_{t=0}^{\Omega}\frac{Z_{i,t}}{\left[1+\rho_i\right]^t} \tag{8}$$

where ρ_i stands for the discount rate of region i and Ω denotes the time horizon. From the Appendix, it is evident that we choose a relatively low discount rate of 1.5 percent, except for CHN and ROW where we assume 3 percent in order not to "overestimate" the incentives of these regions in climate change policies. The strategy vector consists of a time path (35 decades[4], starting in 1990) for emission abatement and investment for all six regions, $s=\{I_{i,t},\mu_{i,t}\}_{i\in N;t=0,\ldots,\Omega}$, and hence is of length 2x35x6=420.

3. Formation of Coalitions

3.1 No Cooperation and Full Cooperation

In this subsection, we consider two benchmarks: no and full cooperation. *No cooperation* means that each region maximizes its *own* lifetime consumption with respect to its own strategy vector, taking the strategies of all other regions as given. The solution is the *N*ash equilibrium strategy vector s^N. From the perspective of coalition formation, this can be interpreted as if each region forms a singleton coalition by itself. In contrast, *full cooperation* maximizes the sum of lifetime consumption over all regions. That is, each region chooses abatement and investment considering not only the effect on its own region but also on all other regions. Because emissions constitute a negative externality[5], the *s*ocially or globally optimal strategy vector s^S differs from the Nash equilibrium s^N. The social optimum can be interpreted as if all regions form one coalition, called the grand coalition. Global abatement is higher in the social optimum than in the Nash equilibrium. However, also in the Nash equilibrium, some abatement is undertaken unilaterally since - compared to the business as usual scenario (BAU) - at least national damages are taken in consideration when choosing the non-cooperative strategy vector s^N.

The difference between Nash equilibrium and social optimum shows up in a very different development of global emissions along the time axis. Whereas Nash equilibrium emissions

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[4] We choose a sufficiently long time period to avoid „end point bias". However, due to discounting, only a shorter period is strategically relevant for players.

[5] The mirror image is: abatement constitutes a positive externality. See in particular subsection 3.2.

follow very closely the business as usual path and grow steadily due to economic growth, social optimal emissions rise only until 2150, level off and decrease afterwards. For instance, in the year 2200, global emissions in the social optimum are only one third of those in the Nash equilibrium. This difference also shows up in the development of carbon concentration as this is illustrated in Figure 1.

Figure 1 about here

In 1990, atmospheric carbon concentration amounts to approximately 750 GtC. BAU-concentration rises steadily and reaches 3443 GtC in 2200. Doubling of concentration with respect to 1990 takes place between 2080 and 2090. The NASH-concentration path follows closely the BAU-path. In contrast, SOCIAL-concentration grows at a much slower rate and reaches 2017 GtC in 2200. Doubling of atmospheric carbon concentration is postponed until some time between 2110 and 2120. The carbon concentration levels off at about 2000 GtC by the year 2200.

Taken together, we may conclude that there is a large difference between no and full cooperation at the global level in ecological terms (emissions and concentration). This is also true at the level of individual countries. Taking averages of abatement efforts over time, we find that CHN abates about 7.70%, followed by EU with 7.24% and USA with 6.44% in the Nash equilibrium. The lowest abatement effort is undertaken by ROW with only 1.45%. World average abatement amounts to 3.74%. For ROW, low abatement is due to strong free-riding incentives within this heterogeneous region.[6] For CHN, high abatement is due to low marginal abatement costs and for EU this is due to their high climate change damage valuation. In the social optimum, world average abatement is 37.14%. CHN and ROW are required to reduce their emissions substantially more than other regions (68.13% and 55.50%, respectively) due to their low marginal abatement costs.

In terms of “potential GDP” (Y_i in equation (1)), differences between Nash equilibrium and social optimum are not very pronounced. This is due to three reasons. First, abatement and damage costs consitute only a small fraction of total production and consumption. Second, negative externalities of carbon emissions occur mainly in the future but receive less weight due to discounting. Third, abatement costs are relatively high compared to the benefits from

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[6] As in Nordhaus/Yang (1996), climate change damage parameter of ROW has been revised downward for all scenarios in which ROW acts as a singleton in order to account for the fact that this region comprises many countries. Without this correction, ROW would produce unrealistically high rates of emission control when it does not cooperate with other regions.

reduced emissions for greenhouse gases, so that also in the social optimum only moderate action is required. Hence, it is not surprising that difference in discounted lifetime world consumption (i.e., global welfare) between the Nash equilibrium (338,060 million \$) and the social optimum (339,831 million \$) – though not small in absolute magnitude (1,771 million \$) – is not big in relative terms (0.52%). The major winners from cooperation are EU (0,924 million \$), USA (0,637 million \$) and JPN (0,315 million \$). Also FSU (0,231 million \$) gains, but CHN (-0,284 million \$) and to a smaller extent ROW (-0,052 million \$) loose. In terms of emission abatement, USA, JPN and EU have to contribute below average to the socially optimal solution, but due to above average marginal damages, they benefit much from joint abatement. This "favorable" incentive structure is particular pronounced for EU. In contrast, CHN and ROW face just the opposite incentive structure that is particular "unfavorable" for CHN. CHN contributes well above average to joint abatement and benefits only very little due to low marginal abatement costs and damages.

3.2 Partial Cooperation

In this subsection, we consider intermediate steps between no and full cooperation. *Partial cooperation* means that a subgroup of regions - at least two regions, but less than all regions - form a coalition. This implies that members of this subgroup (i.e., non-trivial or non-singleton coalition) maximize the sum of their members´ lifetime consumption. That is, each member chooses its strategy vector considering the effect on its coalition, but ignores the effect on outsiders. Outsiders are assumed to act as singletons, as described in the non-cooperative equilibrium. Hence, the equilibrium strategy vector s^P can be interpreted as "*p*artial Nash equilibrium between the coalition and outsiders" (Chander/Tulkens 1997). Table 1 gives an overview of possible coalition structures that are partitions of players with one coalition S and the remaining players acting as singletons, c=(S, 1, ..., 1).

Table 1 about here

The first and the last coalition structure represent no and full cooperation (corresponding to Nash equilibrium and social optimum), respectively; the second to fifth coalition structure represent partial cooperation (see column 1). In the context of 6 players, there are 15 possibilities to form a coalition of two members, 20 possibilities to form a coalition of three members and so on and so forth (see column 2). Overall, there are 58 different coalition structures. For reference reason, we number coalition structures consecutively, starting with the coalition structure comprising only singletons and finishing with the coalition structure comprising the grand coalition (see column 3).

In Table 2, we display a selection of coalition structures and their associated welfare and ecological implications. Coalition structures are listed in descending order of global welfare (discounted lifetime consumption). Welfare, concentration and emissions are measured in relative terms, that is, by how much they “close the gap” between the social optimum and the Nash equilibrium. From Table 2, the following conclusions emerge.

The commonly hold view that a high participation indicates success of an IEA proves to be wrong. For instance, coalition structure no. 57 comprises a coalition of five regions but ranks lower than many coalition structures comprising coalitions of 3 or 4 members coalitions, and even lower than coalition structure no. 5, including a coalition of only JPN and ROW. Thus, the identity of members may matter more than the number of participants for the success of cooperation.

From a brief glance of the first 15 ranked coalition structures, it is evident that, as a tendency, the importance of membership decreases along the following sequence: ROW, CHN, EU, USA, FSU and JPN. ROW´s and CHN´s important role stems from the fact that they can provide cheap abatement. Similar, JPN´s low importance is due to expensive abatement. However, there is also an additional dimension related to environmental damages. The higher marginal damages of a coalition member are, the higher joint abatement efforts will be, anything else being equal. This explains the importance of EU and USA compared to FSU and JPN. Therefore, it is not surprising that the “old Kyoto coalition” comprising USA, JPN, EU and FSU (no. 50) ranks relatively low since the two key players CHN and ROW are outsiders. A similar conclusion applies to the “new Kyoto coalition” (no. 28) after the withdrawal of USA. It is evident that this decision implies a dramatic drop in welfare and ecological variables, almost to non-cooperative levels.

Table 2 about here

Despite our qualification about participation and membership, it is evident that all coalition structures different from the singleton coalition structure no. 1 generate higher global welfare (and lower global emissions and concentration). This is due to two important properties of coalition formation that apply to our model. The first property is called superadditivity. *Superadditivity* means that if a region joins a singleton or a coalition, *aggregate* welfare of all regions that are involved in this merger increases. In other words, there is a “coalitional gain” from cooperation. The second property is called positive externality. *Positive externality* means that if a region joins a singleton or a coalition to form a bigger coalition, all outsiders that are not involved in this merger benefit from the merger.

Both properties imply that *global welfare* is higher in any coalition structure different from that consisting of only singletons. This applies also to the welfare of *individual region*s that remain *singletons*. The most favorable condition for a singleton is if all other regions form a coalition. However, despite superadditivity holds, individual regions that are *members of a coalition* may be *worse off* than in the Nash equilibrium. This has already been illustrated for the grand coalition in subsection 3.1, but is also true for partial cooperation. Only 10 out of 56 coalition structures that constitute partial cooperation are *individually rational*, i.e., imply no loss to any member compared to the Nash equilibrium. None of the top 15 ranked coalition structures in Table 2 are individually rational. This also applies to the "old and new Kyoto coalition". Not a single coalition including CHN as a member is individually rational, confirming the unfavorable incentive structure of this country already identified for full cooperation. From Table 1, it is evident that no coalition with 5 members and only one with 4 members is individually rational. This finding stresses the large asymmetries between regions. It also suggests that without transfers cooperation will prove to be very difficult. In particular, without transfers, a key player of cheap abatement, namely CHN, can hardly be convinced to join a climate treaty.

4. Stability of Coalitions

4.1 A First Approach

In this subsection, we have a first look at the stability of coalition structures. Clearly, a necessary condition for stability is individual rationality. Due to the positive externality property, a coalition member that receives a lower welfare than in the singleton coalition structure will gain by leaving the coalition[7]. However, even if individual rationality holds, a coalition member may have an incentive to leave its coalition which is not the case provided the following condition holds:[8]

internal stability: $w_i(S) \geq w_i(S \setminus \{i\}) \quad \forall\, i \in S$ (9)

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[7] After leaving, a region can free-ride on the efforts of the remaining coalition. Due to the positive externality property, the deviator will be better off than in the singleton coalition structure.

[8] The concept of internal&external stability is due to d´Aspremont et al. (1983). It has been frequently applied to study stability of IEAs (e.g., Barrett 1994, Cararro/Siniscalco 1993 and Hoel 1992) and belongs to non-cooperative coalition theory. For an overview of other non-cooperative concepts see Bloch (1997) and Yi (1997) in the general context and Finus (2001 and 2003) in the context of IEAs. For applications of concepts of cooperative coalition theory see for instance Chander/Tulkens (1997) and Germain/Toint/Tulkens (1998).

If a coalition member i leaves coalition S to become a singleton, it saves abatement costs. However, not only the deviator will reduce its abatement effort but also the remaining regions in coalition $S \setminus \{i\}$ will abate less, leading to an increase of damages in each region. The importance of both welfare effects determines the incentive of remaining in or leaving coalition S. As a tendency, given a coalition S, the more regions join S, the higher the incentive of current members to leave their coalition will be. The reason is that more members mean higher abatement and hence higher abatement costs and lower damages. Hence, the incentive to leave a coalition increases gradually due to the convexity of abatement cost functions and the concavity of benefits from reduced damages. However, there is also a second dimension of stability:

external stability: $w_j(S) \geq w_j(S \cup \{j\}) \quad \forall\, j \notin S$ (10)

External stability is the mirror image of internal stability: no singleton should have an incentive to join coalition S. The advantage of joining is that damages drop: global abatement increases and, in particular, own efforts are matched by those of other members. However, higher abatement means also higher abatement costs. Again, the importance of both welfare effects determines the incentive of joining coalition S or remaining an outsider. For the same reason as mentioned above, as a tendency, the more regions already joined coalition S, the less attractive it becomes to follow suit.

Testing for stability, it turns out that 9 out of 11 individually rational coalition structures are internally stable. Since the singleton coalition structure is internally stable by definition, this implies that 8 out of 10 coalition structures that constitute genuine partial cooperation are internally stable. Those coalition structures are indicated bold faced in Table 1. Interestingly, the two individually rational coalition structures out of ten that are not internally stable are exactly those with “best performance” in terms of global welfare, global emissions and concentration. This confirms the fundamental forces mentioned above: the free-rider incentive increases with the level of abatement.

Unfortunately, none of the 9 internally stable coalition structures is externally stable. Hence, partial cooperation is not stable – at least without transfers and/or a change of institutional rules.

4.2 A Second Approach: Transfers

4.2.1 Preliminaries

From the previous discussion it became evident that a necessary condition for internal stability is individual rationality that is frequently violated because of large asymmetries between regions. Thus, an obvious way out of this dilemma seems to be transfers. For instance, consider a coalition structure $c = (S,1,1,\ldots,1)$ and assume that each coalition member $i \in S$ receives additionally to its welfare $w_i(c)$ a transfer $t_i(c)$ of the following type:

$$t_i(c) = \left[w_i(c^N) - w_i(c)\right] + \lambda_i \sum_{i\in S}\left[w_i(c) - w_i(c^N)\right] \tag{11}$$

where $w_i(c^N)$ is the welfare level in the Nash equilibrium, corresponding to the coalition structure with only singletons $c^N = (1,1,\ldots,1)$. The first term on the left hand side in (11) puts everybody back to its Nash equilibrium payoff, the second allocates the aggregate gain to the coalition from cooperation to its members where λ_i is a weight, $1 \geq \lambda_i \geq 0$, $\sum_{i\in S}\lambda_i = 1$. Substituting (11) into $\hat{w}_i(c) = w_i(c) + t_i(c)$ gives:

$$\hat{w}_i(c) = w_i(c^N) + \lambda_i \sum_{i\in S}\left[w_i(c) - w_i(c^N)\right] \tag{12}$$

Because $\sum_{i\in S}[w_i(c) - w_i(c^N)] > 0$ is true due to superadditivity, every member is better off than in the Nash equilibrium. Note that (12) can be interpreted as the outcome of a Nash bargaining solution. The “standard” Nash bargaining solution is a special case where $\lambda_i = 1/\#S$ - that is, equal sharing. However, one may also consider different weights that are typically interpreted as bargaining power in the game theoretic literature. Below, we consider several transfer schemes of the form in (11) that have been proposed in the literature and which differ in terms of weights. There, however, weights are usually not interpreted from a positive but more from a normative point of view.

4.2.2 Motivation and Fundamental Features

There is a long tradition in the literature to consider different transfer rules in the context of international environmental problems. On the one hand, the empirical literature has given much attention to the moral and philosophical motivation of various rules (Rose/Stevens 1998, Rose et al. 1998 and Stevens/Rose 2002). However, most studies consider only welfare effects in terms of abatement costs, giving only an incomplete picture of the gains from cooperation, letting alone the incentive to form self-enforcing agreements. Only a few studies consider also the dimension of damage costs and check stability. However, typically, they consider only a small portfolio of well-known bargaining rules (e.g., Nash bargaining solution with equal weights or Chander/Tulkens transfer rule; see, e.g., Botteon/Carraro 1997 and Germain/Toint/Tulkens 1998).[9] On the other hand, the theoretical literature has either assumed symmetric players, rendering transfers redundant, or assumed a very particular form of asymmetry (e.g., two types of countries) with only one or two transfer schemes (e.g., Barrett 1997 and Hoel 1992). Therefore, it is one of the purposes of this paper to consider a large variety of transfer schemes, studying their effects on coalition formation and stability with an empirical model.

In the following, we first discuss the input data to compute weights of the various transfer schemes. Then we introduce our transfer schemes, briefly mention their motivation, but refer the reader for a more detailed description to the empirical literature mentioned above. The discussion is illustrated in Table 3.

Table 3 about here

The first three rows of Table 3 show the base data on gross domestic product (GDP_i), population (POP_i) and emissions (E_i) for the base year 1990 as it enters our model (see Appendix). This base data is also used as input to compute weights of the different transfer schemes. Rows four to six show some commonly used indicators of economic and ecological performance of different regions. Emissions per capita (E_i/POP_i) illustrates that USA citizens are the largest and ROW citizens the smallest emitters per head. GDP per capita (GDP_i/POP_i) indicates that CHN is the poorest and JPN the richest region in our model. Emissions per unit of GDP (E_i/GDP_i) is a commonly used indicator to measure energy efficiency. It is evident that the Japanese is the most and the Chinese the least energy efficient economy.

We now turn to the different scenarios. Scenario 0 is the benchmark case without transfers and scenario 1 to 8 represent different transfer schemes, resulting from different weights. Column 1 lists the numbers and names that we attach to each scenario and column 2 provides the formula for computing weights λ_i. Subsequent columns display weights (λ_i) and transfers (t_i) under the assumption of the grand coalition. This gives a rough indication of the welfare implications of different scenarios, though the values will differ for other coalition structures with partial cooperation. We also display the number of violations of internal stability in terms of region i (VIS_i), considering all 58 coalition structures. Since there are 31 coalition structures where region i is a member of a coalition of at least two members, the maximum number of possible violations is 31. Again, the number of violations can only be a

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[9] An exception is for instance Bosello/Buchner/Carraro (2003).

crude and first indication of stability implications of different scenarios. For instance, the absence of transfers (scenario 0) favors in particular EU (VIS_i=0) and puts CHN (VIS_i=31) at a big disadvantage, confirming observations above. For coalition formation, this has two implications. Either only regions with a similar incentive structure, e.g., USA and JPN or FSU and ROW can form a stable coalition, or asymmetries have to be balanced via transfers.

Scenario 1 assumes equal weights. That is, each member receives the same share from the gains from cooperation. This solution may be seen a focal point of fairness in the sense of Schelling (1960). However, it treats all participants equally, regardless, how much they contribute to cooperation and regardless of the size or other characteristics of their economy. This is different in scenario 2 where weights are related to population. The normative idea behind this rule may be summarized as: “one man one vote”. We call scenario 1 and 2 “egalitarian 1” and “egalitarian 2”. For the grand coalition, “egalitarian 1” means a larger share of the gains from cooperation for CHN and ROW compared to “no transfers”. This initiates transfers from USA, JPN and EU to CHN, FSU and ROW. That this means a substantial redistribution of welfare, and, in fact, again, an asymmetry, but opposite to that in the no transfer case, is evident from the change of the number of “VIS”. A similar but even a more pronounced pattern holds for “egalitarian 2” because population is strongly concentrated in CHN and ROW.

Scenario 3 relates weights to the inverse of the emission per capita ratio and scenario 4 does this with respect to the inverse of the GDP per capita ratio. Scenario 3´s motivation is that every man should have the same “right to pollute”. It is also associated with historical responsibility for the current stock of greenhouse gases. Since USA has the highest emission per capita ratio, they receive the lowest weight and because this is completely reversed for CHN and ROW, both regions receive high weights. Scenario 4 allocates the gains from cooperation to the “poor” and thus uses environmental policy as a vehicle to transfer money from the “rich” to the “poor”. The parameter η is usually referred to as the “degree of inequality aversion”. We consider three values were $\eta \to +\infty$ would correspond to the “Rawlsian maximin rule”. In our model, already $\eta = 10$ approximates this rule since all weights are zero, except China´s weight that is 1 in the grand coalition. However, even a value of “only” $\eta = 0.25$ implies a substantial reshuffling of the gains from cooperation from the “rich” to the “poor”. We follow the literature and call scenario 4 “ability to pay” and because of its similar design scenario 3 “ability to pollute”. Again, “extreme” weights in scenario 3 and 4 show up in a high number of “VIS_i” in industrialized countries and low numbers for developing countries and economies in transition.

Scenario 5 and 6 are related to the ecological dimension and are therefore called "ecological reward" and "ecological subsidy", respectively. Both scenarios relate weights to energy efficiency that is measured as "emissions per output". "Ecological reward" means that those regions with a high energy efficiency receive a high share of the gains from cooperation whereas this is just the opposite with "ecological subsidy". Whereas the motivation for rewards is more or less self-evident, the motivation for subsidies has to argue that dirty regions should receive sufficient resources to clean up their environment. Not surprisingly, energy efficiency is very high in JPN and EU but very low in CHN and FSU. Due to low emissions associated with its low stage of economic development, ROW´s energy efficiency is relatively high.

Scenario 7 and 8 are the mirror images of scenarios 3 and 4. Whereas scenarios 3 and 4 implied a major redistribution of the gains from cooperation based on "ecological or welfarian justice", scenario 7 and 8 more or less preserve the "status quo". That is, these transfer schemes acknowledge "political reality" that huge transfers are politically not feasible.

Overall, Table 3 suggests that except for the "pragmatic solutions" "status quo 1" and "status quo 2", the amount of transfers may be very large which is evident by comparing the total amount of transfers under the various scenarios (last column) and recalling that the total gain from cooperation amounts to 1,771 million \$.[10] It is already evident that many transfer schemes, though they may be grounded on well-defendable moral motives, change the asymmetry of the no transfer scenario, but may introduce another asymmetry. In particular, the high and very concentrated violations of internal stability under some scenarios already indicate that some transfer schemes may be regarded as "just" but may not be very useful in encouraging a high voluntary and self-enforcing participation.

4.2.3 Results

Table 4 lists internal and externally stable coalition structures that are stable under at least one scenario. A "X" means that this coalition structure is internally and externally stable (as defined in section 4.1) under a particular scenario; what "**X**" means will be explained in section 4.3.

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[10] „Total" transfers in the last column of Table 3 are the sum of all positive transfers (=sum of all negative transfers) but not of all transfers that would be zero by definition. Total transfers are an indicator of the amount of financial resources redistributed by the transfer scheme. It is important to note that because transfers are computed according to (11) it can happen that total transfers exceed the total gain from cooperation. (For instance, suppose $w_i(c^N) - w_i(c) > 0$ and $\lambda_i = 1$, then $t_i(c) > \sum_{i\in S}\left[w_i(c) - w_i(c^N)\right]$).

Whereas in the no transfer case no coalition was stable, now at least one coalition structure is stable under each scenario. With exception of scenario 4c, only one or two coalition structures are stable. No coalition larger than 3 members is stable and most stable coalitions comprise only two members. This stresses that individual rationality is a necessary but by no means a sufficient condition for stability. Also with transfers, the free-rider incentive increases with the size of coalitions. Nevertheless, also small coalitions can make a difference by closing the gap between social optimum and Nash equilibrium under most scenarios by 50 or more percent. This confirms a central result obtained from the game theoretical literature on international environmental agreements: when the difference between social optimum and Nash equilibrium is small, coalitions are able to close this gap more successfully than when this gap is large.[11] As argued in section 3.1, in our model this difference is small and amounts to only 0.52 percent in welfare terms.

It is interesting to observe that no coalition including only the key industrialized regions USA, JPN and EU is stable. Hence, neither the "old" nor the "new" Kyoto coalition is stable. Moreover, scenario 1 to 4b and 6 do not involve any of the key industrialized regions, but only FSU, CHN and ROW. This indicates that it is not that straightforward to establish stable cooperation between industrialized countries, countries in transition and developing countries through morally motivated transfers. As conjectured already in the previous subsection, this is partly due to the fact that most transfers replace one asymmetry by another. Therefore, it is not surprising that "mixed membership" is found for the two status quo scenarios. Under most scenarios, the number of violations VIS_i as listed in Table 3 already provides a good indication which regions participate in a stable coalition as listed in Table 4: only regions with a low VIS_i number form stable coalitions.

However, whereas asymmetries hamper internal stability, they foster external stability. For instance, as observed in the previous subsection, scenario 1 favors CHN, FSU and ROW at the expenses of USA, JPN and EU. Therefore, the coalition between CHN, FSU and ROW is externally stable because no key industrialized country has an incentive to join this coalition.

4.3 A Third Approach: Changing Membership Rules

4.3.1 Introduction

In subsection 4.1, it became evident that only 9 coalition structures are internally stable in the case of no transfers of which none is externally stable. Clearly, since participation is volun-

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[11] Barrett (1994) called this finding a paradox. For a summary, see Finus (2003).

tary, it seems difficult to challenge the condition of internal stability. Of course, one could argue that if after a region leaves its coalition and the remaining members were to punish the culprit harsh, stability would be easier to enforce. Though this is certainly true, punishment must also be credible. In our model, the remaining regions reoptimize their strategies after a deviation, typically meaning that they revise their abatement targets downward. However, they choose their equilibrium strategy, which is a best reply under the "new" condition, but not a strategy that hurts the free-rider at any cost to punishers.

Alternatively, however, one may consider a change of the condition of external stability. Taken literally, external stability means an *open membership rule* where every outsider can join the coalition without asking for acceptance. However, suppose membership is exclusive and that current members of a coalition vote either by majority or unanimity voting about accession of a new member. Such voting procedures, though usually not known from international environmental agreements, are frequently part of many other international treaties, like for instance WTO, European Union and Security Council. Nevertheless, there seems a priori no reason why such alternative rules should not be considered. Basically, such a change may be interpreted as changing the typical rule for public goods to rules typical for club goods.

It is easy to see that such a change may imply that some internally stable coalitions that are externally unstable under open membership may become externally stable under exclusive membership. Thus, the interesting question is whether "more stability" translates into higher global welfare. Before doing so, it is important to pause for a second and to realize that a change of membership is not just a "technical" trick. For instance, it could be argued that current members never turn down an application because more members means more contributors to cooperation. However, in our model, a coalition $S \cup \{i\}$ increases abatement efforts compared to coalition S, which may be regarded as "too ambitious" by at least some of the current members. Consequently, one could argue that all current members of S could just allow i to join, asking it to increase its abatement effort, but that all members S do not change their economic strategies. Alternatively, one could argue that i must not join coalition S, but may just increase its abatement effort, which current members neither can avoid nor they have an interest to do so. However, both alternatives can never be in the interest of the "potential accessor" i. The reason is simple: under coalition structure c=(S, 1, ..., 1), $s = (s_i, s_{-i})$ is the equilibrium economic strategy vector that implies that s_i is a best reply to s_{-i} (and vice versa). Consequently, if under coalition structure $c' = (S \cup \{i\}, 1, ...1)$ s_{-i} is the same as under c=(S, 1, ..., 1), it cannot be an improvement for i to change its strategy to s_i' when joining coalition S. A similar argument applies if i only changes its strategy without joining coalition S.

4.3.2 Results

In Table 4, “**X**” indicates stable coalition structures under exclusive membership where we restrict attention to unanimity voting. In the case of no transfers (scenario 0), the impact is dramatic. Now seven coalition structures are stable where the most successful achieves a welfare level of 60.7 percent. Also for the various transfer schemes the maximum welfare is usually raised, though the changes are not so pronounced as in the case of no transfer. The largest difference can be observed for scenario 7, Status Quo 1. Obviously, exclusive membership makes not much difference for scenarios 1 to 4c because industrialized regions have no interest anyway in joining non-industrialized regions.

Taken together, the results stress that institutional rules may be as important as transfers for the stability of international environmental agreements. In particular, if transfers are not available, difficult to implement or politically not feasible, then a change of institutional rules may be an alternative measure to increase the success of cooperation. This is even more true when considering such institutional changes involve basically no costs. Moreover, now with exclusive membership, morally motivated transfer schemes (scenario 1 to 6) are with one exception inferior in welfare terms to no transfers and the two status quo rules. This indicates that in a second-best-world with free-rider incentives moral motives may not always be a good guide to establish effective agreements.

5. Summary, Conclusion and Discussion

Our approach is novel in the sense that we combine rigorous game theoretic analysis of coalition formation with numerical simulations in the context of global warming. The cost-benefit analysis was based on a dynamic integrated assessment model that captures the feedback between the economy, environmental damages and the climate system. The model comprises six world regions: USA, Japan, European Union, China, Former Soviet Union and “Rest of the World”. Stability of coalitions was tested with the concept of internal and external stability. From our simulations seven key results emerged. First, in the context of global warming, the difference between full and no cooperation is large in ecological terms but small in welfare terms. This is because abatement costs are large compared to estimated damage costs, both costs constitute a small portion in relation to production and consumption and benefits from abatement occur in the far future. Second, though stable coalitions are only small, they can close this small gap by a considerable amount. We recognized that this conclusion is in line with theoretical findings of simpler models on international environmental agreements. Third, membership or identity may be more important for partial cooperation than a high degree of participation. Coalitions that do not comprise key players with low marginal abatement costs (e.g., CHN) and/or high marginal damages (e.g., EU and ROW) will not achieve much at the global level. This result indicated that concluding success only from participation without measuring the effectiveness of an agreement may be misleading. Fourth, without transfers and under open membership rule no stable coalition exists. This stressed that cooperation proves difficult because of large asymmetries between regions. Fifth, the success of cooperation improves through transfers, though no more than three out of six world regions participate in stable cooperation. Thus, making agreements profitable through transfers is a necessary but by no means a sufficient condition to establish successful self-enforcing treaties. Strong free-rider incentives are an obstacle to higher participation and success. Sixth, changing the institutional design from open to exclusive membership can make a big difference and may be as important as transfers. This indicates that in future environmental treaties open membership should not be taken for granted despite it may seem an obvious rule in the context of public goods. Seventh, moral motives may not always be a good guide to establish effective agreements if they are not in line with fundamental free-rider incentives.

Evidently, models are limited in their applicability. From a positive view point and with reference to the Introduction, we mention three aspects. First, technical restrictions forced us to restrict the number of agents to only six where in reality we roughly count 200 countries. In particular, the level of aggregation of ROW is very high that may lead to an overestimation of the prospectives of stable cooperation (see section 3, in particular, footnote 6). Second, our integrated assessement model CWSM, as well as most CGE-models analyzing climate change, assumes damages to be certain. On the one hand, this may lead to an overestimation of the incentives of cooperation. On the other hand, there are voices that claim that damage estimates in RICE (that are the basis of CWSM) are too low, see Kaufmann, 1997. Moreover, provided some agents would attach some probability to uncertain catastrophic events caused by global warming, then our assumptions imply an underestimation. Third, also our long time horizon may overestimate the forsight of politicans. However, a much shorter period would simply ignore the climate problem and would provide no incentive for cooperation at all. Moreover, discounting adjusts "too much" forsight downward. From a normative point, the limitations are less severe when focusing more on the qualitative instead on the quantitative results, which seems sensible given the uncertainty associated with cost-benefit data.

For future research we would like to mention two of certainly many possible options. First, it would be interesting to gain more theoretical insights how transfer schemes should be designed so that they neutralize free-rider incentives in an "optimal way". Second, in the absence of transfers, it would be interesting to analyze how abatement duties should be allocated to improve upon the success of self-enforcing treaties. This may well imply less ambitious abatement targets and/or departure from an efficient abatement allocation within a coalition if this is compensated by a larger participation.

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Appendix

The CLIMNEG World Simulation Model comprises the following equations:

$$\begin{aligned}
Y_{i,t} &= Z_{i,t} + I_{i,t} + Y_{i,t} C_i(\mu_{i,t}) + Y_{i,t} D_i(\Delta T_t) \\
Y_{i,t} &= a_{i,t} K_{i,t}^{\gamma} L_{i,t}^{1-\gamma} \\
C_i(\mu_{i,t}) &= b_{i,1} \mu_{i,t}^{b_{i,2}} \\
D_i(\Delta T_t) &= \theta_{i,1} \Delta T^{\theta_{i,2}} \\
K_{i,t+1} &= \left[1-\delta_K\right] K_{i,t} + I_{i,t} \qquad K_{i,0} \text{ given} \\
E_{i,t} &= \alpha_{i,t} \left[1-\mu_{i,t}\right] Y_{i,t} \\
M_{t+1} &= \left[1-\delta_M\right] M_t + \beta \sum_{i\in N} E_{i,t} \quad M_0 \text{ given} \\
F_t &= \frac{4.1 \ln(M_t/M_0)}{\ln(2)} + F_t^x \\
T_t^0 &= T_{t-1}^0 + \tau_3 \left[T_{t-1}^a - T_{t-1}^0\right] \\
T_t^a &= T_{t-1}^a + \tau_1 \left[F_t - \lambda T_{t-1}^a\right] - \tau_2 \left[T_{t-1}^a - T_{t-1}^0\right] \\
\Delta T_t &= \frac{T_t^a}{2.50}
\end{aligned}$$

Table A1: List of Variables

$Y_{i,t}$	production (billion 1990 US$)
$Z_{i,t}$	consumption (billion 1990 US$)
$I_{i,t}$	investment (billion 1990 US$)
$K_{i,t}$	capital stock (billion 1990 US$)
$C_{i,t}$	cost of abatement (billion 1990 US$)
$D_{i,t}$	damage from climate change (billion 1990 US$)
$E_{i,t}$	carbon emissions (billion tons of C)
$\mu_{i,t}$	emission abatement
M_t	atmospheric carbon concentration (billion tons of C)
F_t	radiative forcing (Watt per m²)
F_t^x	exogenous radiative forcing (Watt per m²)
T_t^a	temperature increase in the atmosphere (°C)
T_t^0	temperature increase in the deep ocean (°C)
ΔT_t	change of temperature increase in the atmosphere (°C)

Table A2: Global Parameter Values

$a_{i,t}$	productivity	RICE
$L_{i,t}$	population	RICE
$\alpha_{i,t}$	emission-output rate	RICE
δ_K	capital depreciation rate	0.10
γ	capital productivity parameter	0.25
β	airborne fraction of carbon emissions	0.64
δ_M	atmospheric carbon removal rate	0.0833
τ_1	parameter temperature relationship	0.226
τ_2	parameter temperature relationship	0.44
τ_3	parameter temperature relationship	0.02
λ	parameter temperature relationship	1.41
M_0	initial carbon concentration	590
T_0^a	initial temperature atmosphere	0.50
T_0^0	initial temperature deep ocean	0.10

Table A3: Regional Parameter Values

	$\theta_{i,1}$	$\theta_{i,2}$	$b_{i,1}$	$b_{i,2}$	ρ_i
USA	0.01102	2.0	0.07	2.887	0.015
JPN	0.01174	2.0	0.05	2.887	0.015
EU	0.01174	2.0	0.05	2.887	0.015
CHN	0.01523	2.0	0.15	2.887	0.030
FSU	0.00857	2.0	0.15	2.887	0.015
ROW	0.02093	2.0	0.10	2.887	0.030

Table A4: Variables in 1990 (Reference Year)*

	Y_i^0	(%)	K_i^0	(%)	L_i^0	(%)	E_i^0	(%)
USA	5,464.796	25.9	14,262.510	26.3	250.372	4.8	1.360	20.5
JPN	2,932.055	13.9	8,442.250	15.6	123.537	2.4	0.292	10.9
EU	6,828.042	32.4	18,435.710	34.0	366.497	7.0	0.872	28.9
CHN	370.024	1.8	1,025.790	1.9	1,133.683	21.5	0.669	3.0
FSU	855.207	4.1	2,281.900	4.2	289.324	5.5	1.066	6.8
ROW	4,628.621	22.0	9,842.220	18.1	3,102.689	58.9	1.700	29.9
World	21,078.750	100.0	54,290.380	100.0	5,266.100	100.0	5.959	100.0

* Y_i^0 and K_i^0 million US$, L_i^0 million people and E_i^0 giga tons.

Figures and Tables

Figure 1: Atmospheric Carbon Concentration ($GtCO_2$)

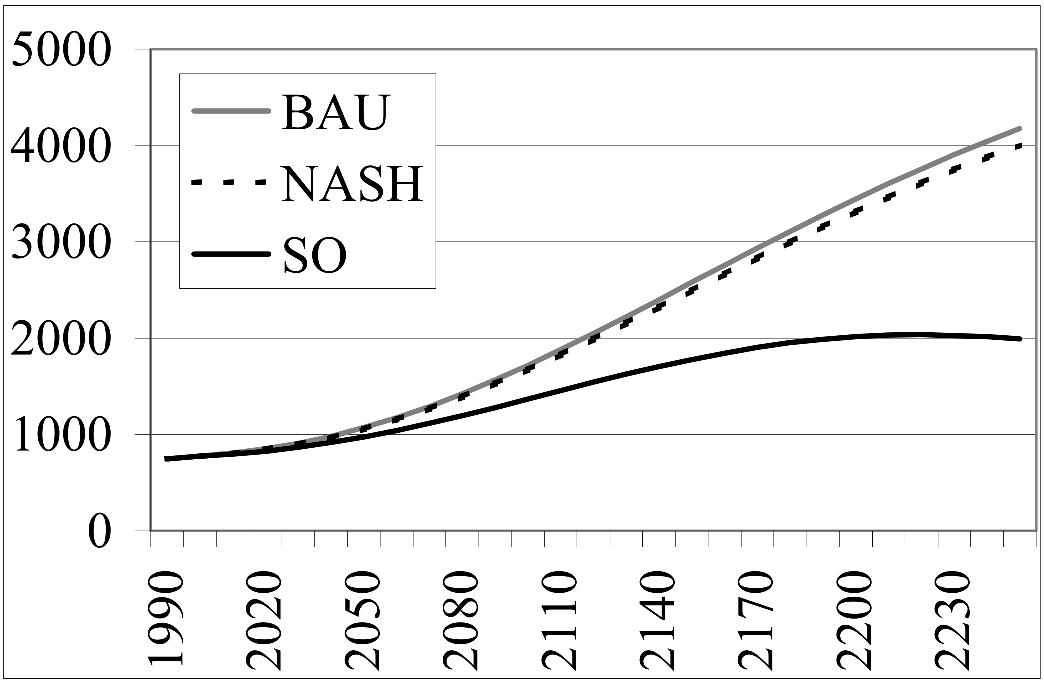

Table 1: Overview of Coalition Structures*

Coalition Structure (1)		Number of Coalition Structures (2)	List of Coalition Structures (3)
1	(1,1,1,1,1,1)	1	**1**
2	(2,1,1,1,1)	15	**2**,3,**4**,**5**,**6**,7,8,9,10,11,12,13,14,15,**16**
3	(3,1,1,1)	20	17,18,**19**,**20**,21,22,23,24,25,26,27,28,29,30,31,32,**33**,34,35,36
4	(4,1,1)	15	37,38,39,40,41,42,43,44,45,46,47,48,49,50,51
5	(5,1)	6	52,53,54,55,56,57
6	(6)	1	58

* Underlined means individually rational and bold means internally stable assuming no transfers.

Table 2: Welfare and Ecological Implications of Different Coalition Structures*

Coalition Structure			Welfare	Concentration	Emissions
Size	Membership	No.			
6	grand coalition	58	100.0	100.0	100.0
5	USA, EU, CHN, FSU, ROW	53	99.1	92.2	93.0
5	USA, JPN, EU, CHN, ROW	56	96.6	90.0	91.1
5	JPN, EU, CHN, FSU, ROW	52	95.6	80.6	81.9
4	USA, EU, CHN, ROW	44	94.5	82.0	83.2
5	USA, JPN, CHN, FSU, ROW	54	93.2	73.2	74.8
4	EU, CHN, FSU, ROW	37	91.3	72.3	73.6
4	JPN, EU, CHN, ROW	41	89.6	69.8	71.5
4	USA, CHN, FSU, ROW	39	87.4	64.1	65.7
4	USA, JPN, CHN, ROW	47	85.9	61.8	63.9
3	EU, CHN, ROW	21	84.0	60.7	62.6
3	USA, CHN, ROW	25	78.8	52.0	54.3
4	JPN, CHN, FSU, ROW	38	78.4	50.3	52.6
5	USA, JPN, EU, FSU, ROW	55	70.3	66.0	67.1
4	USA, EU, FSU, ROW	43	69.1	61.0	62.0
…	…	…	...	...	...
2	JPN, ROW	5	46.4	24.7	26.8
5	USA, JPN, EU, CHN, FSU	57	31.0	26.9	27.5
4	USA, EU, CHN, FSU	45	29.0	24.5	25.0
…	…	…	...	...	...
4	USA, JPN, EU, FSU („old Kyoto“)	50	5.07	1.58	2.14
…	…	…	...	...	...
3	JPN, EU, FSU (“new Kyoto”)	28	2.9	0.7	1.0
…	…	…	...	...	...
2	JPN, EU	14	0.6	0.2	0.3
1	only singleton coalitions	1	0.0	0.0	0.0

* Size: size of coalition S in coalition structure c=(S, 1, ..., 1); membership: only members in coalition S are listed; welfare: discounted global lifetime consumption integrated over 1990-2300; emissions: global emissions integrated over 1990-2300; concentration: atmospheric carbon concentration at t=2300. Welfare, emission and concentration levels are expressed as the relative difference between these levels in a coalition structure and in the social optimum and the difference between Nash equilibrium and social optimum.

Table 3: Background Information of Scenarios

			USA	JPN	EU	CHN	FSU	ROW	Total
Indicators		E_i/POP_i	5432	2364	2379	590	3685	548	1132
		GDP_i/POP_i	21827	23734	18630	326	2956	1492	4003
		E_i/GDP_i	249	100	128	1808	1246	367	283
Scenario 0: No Transfers	-	λ_i	-	-	-	-	-	-	-
		t_i	-	-	-	-	-	-	-
		VIS_i	3	3	0	31	18	12	67
Scenario 1: Egalitarian 1	$\lambda_i=1/\#S$	λ_i	0.17	0.17	0.17	0.17	0.17	0.17	1
		t_i	-341	-20	-629	579	64	347	990
		VIS_i	25	15	26	0	4	0	70
Scenario 2: Egalitarian 2	$\lambda_i=\frac{POP_i}{\sum_{i\in S} POP_i}$	λ_i	0.05	0.02	0.07	0.22	0.05	0.59	1
		t_i	-552	-273	-801	665	-134	1096	1761
		VIS_i	25	26	24	0	22	0	97
Scenario 3: Ability to Pollute	$\lambda_i=\frac{[E_i/POP_i]^{-1}}{\sum_{i\in S}[E_i/POP_i]^{-1}}$	λ_i	0.04	0.09	0.09	0.35	0.06	0.38	1
		t_i	-569	-159	-770	907	-132	723	1630
		VIS_i	26	22	24	0	22	0	94
Scenario 4a: Ability to Pay (η=0.25)	$\lambda_i=\frac{[GDP_i/POP_i]^{-\eta}}{\sum_{i\in S}[GDP_i/POP_i]^{-\eta}}$	λ_i	0.11	0.10	0.11	0.30	0.17	0.21	1
		t_i	-450	-132	-730	818	76	418	1312
		VIS_i	25	23	26	0	7	0	81
Scenario 4b: Ability to Pay (η=1)		λ_i	0.01	0.01	0.01	0.73	0.08	0.16	1
		t_i	-617	-297	-902	1572	-89	334	1906
		VIS_i	25	26	25	0	15	0	91
Scenario 4c: Ability to Pay (η=10)		λ_i	0.00	0.00	0.00	1.00	0.00	0.00	1
		t_i	-637	-315	-925	2055	-231	52	2107
		VIS_i	26	26	25	0	22	15	114
Scenario 5: Ecological Reward	$\lambda_i=\frac{[E_i/GDP_i]^{-1}}{\sum_{i\in S}[E_i/GDP_i]^{-1}}$	λ_i	0.16	0.39	0.30	0.02	0.03	0.11	1
		t_i	-363	370	-391	322	-177	238	930
		VIS_i	22	0	15	10	26	1	74
Scenario 6: Ecological Subsidy	$\lambda_i=\frac{E_i/GDP_i}{\sum_{i\in S}E_i/GDP_i}$	λ_i	0.06	0.03	0.03	0.46	0.32	0.09	1
		t_i	-524	-269	-867	1105	335	219	1660
		VIS_i	25	26	26	0	1	8	86
Scenario 7: Status Quo 1	$\lambda_i=\frac{GDP_i/POP_i}{\sum_{i\in S}GDP_i/POP_i}$	λ_i	0.36	0.16	0.16	0.04	0.25	0.04	1
		t_i	5	-36	-644	354	204	117	679
		VIS_i	2	15	25	0	0	12	54
Scenario 8: Status Quo 2	$\lambda_i=\frac{E_i/POP_i}{\sum_{i\in S}E_i/POP_i}$	λ_i	0.32	0.34	0.27	0.01	0.04	0.02	1
		t_i	-76	295	-446	292	-156	91	678
		VIS_i	7	0	22	23	25	16	93

Legend: Indicators are calculated using base data in Table A4 (Appendix) with $GDP_i = Y_i^0$ (gross domestic product), $POP_i=L_i$ (population) and $E_i = E_i^0$ (emissions). Emissions per capita (E_i/POP_i) are measured in kilogram carbon per capita, GDP per capita (GDP_i/POP_i) in US\$ per capita and emission intensity of GDP (E_i/GDP_i) in gram carbon per US\$. λ_i: weight of transfer scheme (see section 4.2.1), t_i : transfer (billion US\$), VIS_i: number of violations of internal stability. „Total“ for transfers in the last column refers to the sum of all positive transfers.

Table 4: Stable Coalition Structures under Open and Exclusive Membership

Coalition Structure			Welfare	No Transfers	Egalitarian 1	Egalitarian 2	Ability to Pollute	Ability to Pay			Ecological Reward	Ecological Subsidy	Status Quo 1	Status Quo 2
								η=0.25	η=1	η=10				
Size	Membership	No.		0	1	2	3	4a	4b	4c	5	6	7	8
3	EU,CHN,ROW	21	84.0										**X**	
3	CHN,FSU,ROW	17	68.3		X,**X**									
3	JPN,CHN,ROW	23	67.6										**X**	
3	USA,FSU,ROW	20	60.7	**X**										
3	USA,JPN,ROW	33	59.0	**X**										X,**X**
2	EU,ROW	4	57.5	**X**			**X**		**X**	**X**	**X**	**X**		**X**
2	CHN,ROW	3	54.6			X,**X**	X,**X**	X,**X**	X,**X**	X,**X**				**X**
3	JPN,FSU,ROW	19	54.2	**X**										
2	USA,ROW	6	54.1	**X**			**X**	**X**	**X**	**X**		**X**		**X**
2	FSU,ROW	2	47.2	**X**			**X**	**X**	**X**	**X**		**X**		**X**
2	JPN,ROW	5	46.4	**X**			**X**	**X**		**X**	X,**X**	**X**		
3	USA,CHN,FSU	26	20.5										X,**X**	
2	EU,CHN	11	18.6							X,**X**				
2	USA,CHN	13	15.5							X,**X**				**X**
2	JPN,CHN	12	9.7							X,**X**				X,**X**
2	CHN,FSU	7	8.7							X,**X**		X,**X**		
2	EU,FSU	8	2.1							**X**				
2	USA,FSU	10	1.8							**X**				
2	USA,EU	15	1.6							**X**				
2	JPN,FSU	9	1.1							**X**				
2	JPN,EU	14	0.6							**X**				
number of stable cs, open membership				0	1	1	1	1	1	5	1	1	1	2
max. welfare of stable cs, open membership				-	68.3	54.6	54.6	54.6	54.6	54.6	46.4	8.7	20.5	59.0
number of stable cs, excl. membership				7	1	1	5	4	4	14	2	5	3	7
max. welfare of stable cs, excl. membership				60.7	68.3	54.6	57.5	54.6	57.5	57.5	57.5	57.5	84.0	59.0

Legend: List of coalition structures that are internally and externally stable in some scenarios. Coalition structures are sorted in descending order of global welfare; welfare measured as “closing the gap index”; see table 2. X means internally and externally stable under open membership, **X** means internally and externally stable under exclusive membership, assuming unanimity voting.

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