The Impact of Surplus Sharing on the Stability of International Climate Agreements

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Summary

This paper analyses stability of coalitions for greenhouse gas abatement for different sharing rules applied to the gains from co-operation. We use a 12-regions model designed to examine internal and external stability of coalitions (STACO). We compare different sharing rules like, for example, grandfathering *(i.e.* sharing proportional to emissions) and a number of so-called equitable rules like, for example, sharing proportional to population or according to historical responsibilities. Due to strong free-rider incentives we find only small stable coalitions for all sharing rules examined. As a general pattern we observe that coalitions consist of regions with low marginal abatement costs, which are attractive partners in any coalition, and regions which have the highest claims according to the respective sharing rule. Furthermore, we find that a grandfathering scheme leads to the largest and – in terms of greenhouse gas abatement – most successful coalition, while many of the equitable rules achieve very little.

Keywords: International environmental agreements, Sharing rules, Stability of coalitions

JEL Classification: D62, D63, Q25

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1 Introduction

The distribution of emission rights ranks high on the international agenda to reach agreements to reduce greenhouse gases (GHGs) and to mitigate climate change. Emission rights in the form of tradable permits are seen as a cost-effective instrument to achieve emission reduction targets for GHGs. However, the introduction of new property rights raises distributional concerns. Grandfathering schemes that allocate tradable permits proportional to emissions in a base year have been criticised for giving advantage to the largest polluters. In the course of the discussion a number of alternative suggestions have been brought forward, summarised by Rose (1992), Barrett (1992), Kverndokk (1995) and Rose *et al.* (1998). Following Rose *et al.* (1998) it is useful to distinguish three different types of rules for equitable sharing: allocation based rules which apply to the initial distribution of emission permits, outcome based rules which apply to the distribution of the net benefits from emission reductions, and process based rules which comprise criteria for fair decision-making.

This paper deals with outcome based sharing rules. But both, our focus and our approach, are different from previous studies of outcome based rules because we do not stipulate the existence of a binding international agreement. Rather we examine the possibility of self-enforcing agreements. In the absence of an enforcing supra-national body an international environmental agreement will have to be self-enforcing (Barrett 1994). In this paper we study the impact of different rules to share the gains from cooperation on the stability of international climate agreements.

International environmental agreements have be described as games of coalition formation and have been studied by Hoel (1992), Barrett (1994), Na and Shin (1998) and others; see Bloch (2003) for a general survey of coalition formation games and Finus (2003) for a survey focusing on international environmental agreements. It is our prime interest in this paper to examine the stability of international climate coalitions under different surplus sharing rules. This problem has not yet received any attention. The work that comes closest to this paper is by Altamirano-Cabrera *et al.* (2004) who consider the impact of permit distribution on coalition stability, *i.e.* they consider allocation based rules. Bosello *et al.* (2003) have examined the impact of "outcome based equity criteria" on coalition stability, however, their equity concept is severely biased; they consider only equality on the abatement cost side and they disregard of the distribution of benefits from abatement completely.

To analyse stability of international climate agreements we employ a cartel formation game with open membership introduced by d'Aspremont *et al*. (1983). The game is a two-stage game. At stage one players decide whether or not to participate in an international agreement.

Those who decide to participate form a coalition.[1] We refer to those who do not participate as singletons. At stage two the coalition behaves like a single player; each singleton region and the coalition set emission reduction levels as an optimal response to others' emissions. For a singleton it is optimal to reduce emissions such that marginal abatement costs equal marginal benefits from a reduction of damages. Since emission reduction is a global public good, it is optimal for a coalition to reduce emissions such that the sum of the marginal benefits of all coalition members equal the marginal abatement costs. Payoffs are calculated from costs and benefits of abatement assuming the coalition employs a given sharing rule. The (subgame perfect) equilibria of the game coincide with the set of stable coalitions; see Finus *et al.* (2003). A coalition is stable if no member has an incentive to leave the coalition (internal stability) and no singleton player has an incentive to join (external stability).

In our specification of the game (see section 4 for details) any coalition of two or more regions will always generate a surplus for its members as compared to the case where all regions are singletons; but it will also generate positive spillovers to non-members. Although there is a surplus, there will still be incentives to free-ride. An important factor determining the free-rider incentives is the distribution of the surplus between coalition members, *i.e.* the sharing rule applied. We determine stable international climate coalitions for eight different sharing rules using a regionalised global model (12 regions) in which marginal costs of and marginal benefits from a reduction of GHGs are specified for each region. The model, called STACO, is designed to analyse the stability of coalitions. It has been introduced by Finus *et al.* (2003) and it has been used in subsequent work by Finus *et al.* (2004) and Altamirano-Cabrera *et al.* (2004).

We find that, in general, coalitions consist of regions with low marginal abatement costs, which are attractive partners in any coalition, and regions which receive the largest share of the coalition surplus under a given sharing rule. While we do not claim that the empirical specification of the STACO model reflects the current knowledge on the impacts of climate change in all details, it reflects the main inter-regional differences of GHG abatement costs and damage costs of climate change. Therefore, our results may be instructive for the future design of climate policies.

The next section introduces a formal model of coalition formation. Stability of international climate coalitions depends on how the gains from cooperation are shared. We assume that sharing is based on claims and a rule how surplus shares are derived from claims. Section 3 discusses the selection of a surplus sharing rule. We go one step beyond the consideration of the *ad hoc* rules presented by Rose *et al.* (1998) and provide a rationale for the use of

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[1] There is only a single coalition ("the cartel") and every player is free to join; this explains the name "cartel formation game with open membership".

proportional sharing. However, an *ad hoc* element remains regarding what constitutes a claim. Section 4 introduces the empirical specification of the model introduced in section 2. Section 5 presents the results of the stability checks for a sample of reasonable claims. Section 6 concludes.

2 Coalition formation and coalition stability

We apply the cartel formation game introduced by d'Aspremont *et al.* (1983) to the case of GHG abatement. The game proposed is a two-stage game where a coalition forms at the first stage; at the second stage abatement decisions are taken. To explain the structure of the game and its most important characteristics we first consider a simple transboundary pollution game without coalition formation (Mäler 1989, Folmer and von Mouche 2000). Then, we introduce coalition formation.

Consider a simple transboundary pollution game. Let $N = \{1, 2, ..., n\}$ be a set of players (regions). Suppose each player i has an initial level of uncontrolled emissions $\overline{e}_i$ and each player adopts a pollution control strategy (abatement level) $q_i \in [0, \overline{e}_i]$. In the case of GHGs abatement q_i is a pure public good. Each player receives benefits b_i from total abatement $q = \sum_{i \in N} q_i$ and incurs costs c_i for own abatement q_i. We assume $\mathrm{d}b_i / \mathrm{d}q > 0$, $\mathrm{d}^2 b_i / \mathrm{d}q^2 \leq 0$, $\mathrm{d}c_i / \mathrm{d}q_i > 0$ and $\mathrm{d}^2 c_i / \mathrm{d}q_i^2 > 0$. Individual payoffs are

$$\pi_i = b_i(q) - c_i(q_i).$$

Further specifications of benefits and costs are provided in section 4. In the equilibrium each player adopts an abatement level q_i which is an optimal response to others' emissions. It holds for each player that marginal benefits equal marginal abatement costs. Under a set of standard assumptions about production and damage cost functions and under a regularity assumption[2] such transboundary pollution game has a unique interior Nash equilibrium if pollution is uniformly distributed (Folmer and von Mouche 2000, Proposition 3). As this condition applies to GHGs we will have a unique Nash equilibrium in a simple (no coalitions) GHG emissions game. Denote the Nash equilibrium abatement of player i q_i^*, then the Nash equilibrium payoffs are

$$\pi_i^* = b_i(q^*) - c_i(q_i^*).$$

This serves as a benchmark for the following.

[2] The regularity assumption guarantees an interior solution. It requires that both, some small amount of emissions and some small amount of abatement, will be beneficial.

We now consider coalition (cartel) formation. At the first stage each player chooses a strategy σ_i from a strategy set $\boldsymbol{\sigma}_i \equiv \{0,1\}$; $\sigma_i = 0$ means that *i* is not joining the coalition; $\sigma_i = 1$ means that *i* is joining the coalition. Denote $K \subseteq N$ the set of *k* coalition members; $|K| \equiv k$. As there is only a single coalition, if any, we will also refer to *K* as a coalition structure. If $k \leq 1$ the singletons coalition structure emerges. Given a non-trivial coalition *K* with $k \geq 2$, the coalition maximises the joint payoff of the coalition members at the second stage. The game played at stage two is the simple transboundary pollution game described above where the coalition *K* and $n-k$ singletons are the players; *i.e.* there are $n-k+1$ players. Hence, (i) the coalition adopts an abatement strategy which is an optimal response to others' emissions; and (ii) each singleton player adopts an abatement level which is an optimal response to others' emissions. Denote *i*'s abatement level under coalition structure *K* by q_i^K. The payoffs are as follows.

For singleton players we obtain the payoffs:

$$\pi_i^K = b_i(q^K) - c_i(q_i^K) \quad \text{for all } i \in N \setminus K .$$

For coalition members a sharing rule applies. A sharing rule assigns a share s_i of the coalition surplus S^K to every coalition member $i \in K$. The coalition surplus S^K is defined as the joint gain of the coalition members compared with their payoff in the benchmark situation of a singletons coalition structure. Formally,

$$S^K = \sum_{i \in K} \left(b_i(q^K) - c_i(q_i^K) \right) - \sum_{i \in K} \pi_i^* .$$

The payoff of a coalition member is given by her benchmark payoff plus her share of the coalition surplus.

$$\pi_i^K = \pi_i^* + s_i \cdot S^K \quad \text{for all } i \in K .$$

An important special case to consider is the case of the grand coalition, $K = N$. The grand coalition will internalise all externalities of GHG emissions and adopt a Pareto efficient abatement strategy. The resulting abatement strategy profile $(q_1^N, \ldots, q_n^N)$ is unique (see Folmer and von Mouche 2000, Theorem 1).

3 Sharing rules

Regions which join an international agreement will do so to secure a benefit from cooperation. Whether there is a benefit for an individual region and how large this benefit will be is a matter of the sharing rule used to distribute the overall benefit within the coalition. Note that, although there is a benefit from cooperation, a coalition might not be stable because the benefit from free-riding is even larger. Hence, a given coalition faces a surplus sharing problem and the rule according to which the surplus is shared is important for the decision of a region whether or not to join.

Formally a surplus sharing problem is a triple $\langle K, \lambda, S \rangle$ where $K \subseteq N$ is a set of k coalition members; $\lambda = (\lambda_1, ..., \lambda_k) \in \mathbb{R}_+^k$ is vector of individual claims of the coalition members; $S \in \mathbb{R}_+$ is the surplus to be shared. Claims are based on characteristics that are considered relevant for the sharing problem. This will be discussed below. Let Ω be the set of all surplus sharing problems. A solution to a surplus sharing problem, called sharing rule, is a mapping $\mathcal{R} : \Omega \rightarrow \mathbb{R}_+^k$, *i.e.* a rule $\mathcal{R}$ assigns a payoff vector $s = (s_1, ..., s_k)$ to every surplus sharing problem $\langle K, \lambda, S \rangle$, and $\sum_{i=1}^{k} s_i = S$. Hence, a sharing rule is always efficient in the sense that it distributes the entire surplus.[3]

Following Moulin (1987) and, particularly, Pfingsten (1991) we require that a sharing rule satisfies the following properties:

Anonymity: For all $i, j \in K$, all $\lambda \in \mathbb{R}_+^k$, and all $S \in \mathbb{R}_+$,
$\lambda_i = \lambda_j \Rightarrow s_i = s_j$.

Surplus monotonicity: For all $i \in K$, all $\lambda \in \mathbb{R}_+^k$, and all $S, S' \in \mathbb{R}_+$,
$S > S' \Rightarrow s_i(K, \lambda, S) \geq s_i(K, \lambda, S')$.

Additivity: For all $i \in K$, all $\lambda \in \mathbb{R}_+^k$ and all $S, S' \in \mathbb{R}_+$,
$s_i(K, \lambda, S + S') = s_i(K, \lambda, S) + s_i(K, \lambda, S')$.

Separability: For all $i \in K$, all $H \subset K$ and $H \neq \emptyset$, all $\lambda, \lambda' \in \mathbb{R}_+^k$, and all $S, S' \in \mathbb{R}_+$,
$\lambda_i = \lambda'_i$ for all $i \in H$ and $\sum_{i \in H} s_i(K, \lambda, S) = \sum_{i \in H} s_i(K, \lambda', S') \Rightarrow s_i(K, \lambda, S) = s_i(K, \lambda', S')$'.

Anonymity requires equal treatment of equals. *Surplus monotonicity* says that no one should loose if the surplus increases. *Additivity* says that payoffs should not change if the surplus is paid out in two instalments instead of one. *Separability* is a subgroup consistency requirement which says that individual payoffs in every subgroup depend only on the claims of the players in the subgroup and the subgroup's surplus. *Anonymity* and *Surplus monotonicity* are hardly debatable. We would argue that *Additivity* applies to the case at hand. As the true damages of climate change and, hence, the true benefits of abatement become known at a later stage, the distribution should not depend upon the pattern of how benefits become available. The case for *Separability* is that it should not matter for the final outcome whether a player receives her

[3] This is a formal definition of a sharing rule when claims are given; in other sections of the paper we use the term "sharing rule" in a broader sense reflecting also claims.

share of the coalition surplus directly or whether payment is received by a subcoalition who then distributes the joint share of the surplus to its members.

Pfingsten (1990) has shown that these properties characterise a family of sharing rules:[4]

PROPOSITION 1 (Pfingsten): A sharing rule $\mathcal{R}$ satisfies *Anonymity*, *Surplus monotonicity*, *Additivity* and *Separability* if and only if $\mathcal{R}$ is either

(i) equal sharing: $s_i(K,\lambda,S)=\frac{1}{k}S$,

(ii) proportional sharing $s_i(K,\lambda,S)=\frac{\lambda_i}{\sum_{j\in K}\lambda_j}S$,

or (iii) a combination of (i) and (ii) $s_i(K,\lambda,S)=\frac{\lambda_i}{\sum_{j\in K}\lambda_j}\alpha S+\frac{1}{k}(1-\alpha)S$,

where $0<\alpha<1$.

As *Anonymity*, *Surplus monotonicity*, *Additivity* and *Separability* are defendable properties for the case of coalitions for GHG abatement, proposition 1 characterises the set of reasonable sharing rules.

In what follows we consider a set of 8 sharing problems which differ with respect to what constitutes a claim. One can apply different rules to these sharing problems (equal sharing, proportional sharing and combinations), our focus is, however, on proportional sharing.

<u>Egalitarian claims:</u> $\lambda_i=\lambda_j$, for all *i*, *j*.

All players (regions) have equal claims. Egalitarian claims seem not to be convincing in the case of climate coalitions of heterogeneous regions. But still we include this case as a benchmark case because proportional sharing under egalitarian claims coincides with equal sharing.

<u>Regional income claims:</u> $\lambda_i=GDP_i$,

where GDP_i is region *i*'s gross national product in a base year. This rule has also been dubbed "horizontal equity" by Rose *et al.* (1998). One appealing feature of the rule is that it maintains relative welfare positions.

<u>Population claims:</u> $\lambda_i=pop_i$,

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[4] In the proof Pfingsten (1991) also uses a property called *No advantageous reallocation* which requires that the coalition surplus is independent of the distribution of claims. This always holds in the GHG abatement game analysed in this paper.

where pop_i is region i's population in a base year. The motivation for this rule is straightforward: If individuals have equal rights to the global commons, gains from cooperation should be distributed evenly across the global population.

Ability-to-pay claims: $\lambda_i = \left(GDP_i / pop_i\right)^{-\gamma}$, $\gamma > 0$.

Regions with a lower per capita income have a larger claim. Under this rule climate policy is used a means to reduce inequality. So the motivation stems from outside climate policy. The distribution may be guided by some principle of "international justice".

Emissions claims: $\lambda_i = e_i$,

where e_i are region i's emissions in a base year. Emissions claims can be interpreted as historical rights.

Inverse emissions claims: $\lambda_i = e_i^{-\gamma}$ with $\gamma > 0$.

Regions with a higher emissions share receive a lower share of the gains from cooperation. These claims reflect historical responsibilities.

Damage cost claims: $\lambda_i = d_i$,

where d_i is the net present value of region i's damages from climate change. After implementation of abatement policies, some damages due to climate change will still remain. Those who suffer larger damages, should receive a larger compensation.

Abatement cost claims: $\lambda_i = c_i$,

where c_i is the net present value of region i's abatement cost. The coalition surplus can be interpreted as a return to abatement investments. Who bears larger costs should be entitled to a larger share of the surplus.

Of course, a longer list of possible claims could be generated. Next to egalitarian claims which serve as a benchmark we include income, population and ability-to-pay claims because they have received extensive discussion by Rose *et al.* (1998). Emissions claims are probably the most prominent and are the outcome based analogue to a grandfathering scheme of emission permits. Inverse emission claims, which reflect historical responsibilities, are less prominent in economic analysis, but they have received some discussion in philosophy (Gosseries 2004, Weikard 2004). We have included damage cost and abatement cost claims because they reflect different views on compensation. Marginal damage cost claims seem worth considering as they have been discussed in the literature (cf. Chander and Tulkens 1995). However, our empirical results are derived using a linear damage cost function. In this case, the use of marginal damage cost claims will lead to the same result as the use of damage cost claims. Marginal abatement cost claims have not been included because the optimal abatement strategy for the coalition requires equal marginal abatement cost for all coalition members; hence, such claims will lead to equal sharing.

4 Empirical model and data

In order to examine the sharing problems described in the previous section we adopt a 12-regions model, called STACO, introduced by Finus *et al.* (2003). STACO considers a baseline scenario of growing emissions over a 100 years time horizon. A discount rate of 2% is used for intertemporal aggregation to calculate the net present values of costs and benefits of abatement.

STACO uses a specification of regional abatement cost functions from Ellerman and Decaux (1998). Marginal abatement costs are specified as $a_i'(q_i) = \xi_i q_i^2 + \zeta_i q_i$, where $\xi_i, \zeta_i > 0$ are regional parameters. The model regions are the following: United States (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 all remaining other countries (ROW). STACO considers constant abatement paths; abatement costs are assumed to be constant over time. Table 1 gives discounted marginal abatement costs for a uniform abatement level across regions (column 2). Furthermore, Table 1 reports emissions reductions for the Nash equilibrium of the singletons coalition structure (column 3), and the corresponding marginal and total abatement costs (columns 4 and 5). Emissions reductions and marginal and total abatement costs are also reported for the grand coalition (columns 6-8). It can be seen from column 2 that, for a uniform abatement level, CHN has the lowest marginal abatement costs followed by USA and FSU while BRA has by far the highest. CHN, USA and FSU have high emissions levels (see Table 2, column 5) and cheap abatement options, while BRA's abatement options are expensive due to low emissions levels. For the singletons coalition structure the picture changes. EET and BRA have the lowest marginal abatement cost while EEC and USA have the highest. In this case each region equates marginal abatement costs with marginal damage costs which causes USA and EEC to adopt high levels of abatement while BRA chooses to abate very little. Under a grand coalition 37 % of the global abatement will take place in CHN since CHN provides the cheapest abatement options. One can presume that CHN is an attractive partner in any stable climate coalition that might emerge.

The STACO model uses a linear approximation of the damage cost function of the DICE model introduced by Nordhaus (1997). Moreover, the damage cost function is rescaled using estimates of Tol (1997). Global benefits from abatement are defined as avoided damages. Regional benefits are calculated as shares of global benefits from abatement based on estimates from Fankhauser (1995) and Tol (1997); see Finus *et al.* (2003). The shares are reported in Table 2, column 7. Because STACO uses a linear benefits function marginal benefits are constant and are reported in Table 1, column 4 (recall that for each region marginal benefits equal marginal abatement costs for the singletons coalition structure).

Table 1: Benchmark cases: singletons coalition structure and grand coalition

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Singletons coalition structure			*Grand coalition*		
Region	*Marginal abatement costs at 50 Mton/year*	*Emissions reduction*	*Marginal abatement costs*	*Total abatement costs over 100 years*	*Emissions reduction*	*Marginal abatement costs*	*Total abatement costs over 100 years*
	($/ton)	(Mton/year)	($/ton)	(bln $)	(Mton/year)	($/ton)	(bln $)
USA	1.40	162.3	8.46	53.33	379	37.4	513
JPN	55.84	7.7	6.45	2.44	36	37.4	63
EEC	5.82	66.2	8.83	24.22	161	37.4	229
OOE	8.94	19.0	1.29	0.82	102	37.4	127
EET	9.56	9.3	0.49	0.18	102	37.4	130
FSU	2.57	49.6	2.52	4.24	193	37.4	242
EEX	9.98	7.9	1.12	0.43	124	37.4	188
CHN	0.59	154.9	2.32	16.09	956	37.4	1,348
IND	3.31	33.6	1.87	2.73	216	37.4	295
DAE	13.20	5.4	0.93	0.24	102	37.4	155
BRA	787.81	0.2	0.57	0.00	7	37.4	12
ROW	4.00	37.2	2.54	3.95	185	37.4	250
World		553.2		108.68	2,563	37.4	3,553

Source: Finus et al. (2003), own calculations.

As explained in section 2 any coalition chooses a level of abatement where marginal abatement costs (for each of the coalition members) equals the sum of the marginal benefits from abatement. Under the STACO specification benefits are linear in abatement. In a transboundary pollution game the following holds:

> PROPOSITION 2 (Folmer and von Mouche): Under linear damage costs (constant marginal damage costs) players have a dominant abatement strategy.

No coalition or singleton will adjust its strategy if others change theirs, because there is no change in marginal damage cost. Proposition 2 states an important feature of the STACO specification. That regions have a dominant strategy in the global pollution game implies that there is no "leakage". Members of a non-trivial coalition will abate more compared with the singletons coalition structure. This additional abatement is *not* offset by less abatement of the remaining singletons, as they have dominant strategies. Note that this feature does not generally apply in a broader class of transboundary pollution games.

The information on benefits and costs of abatement described above is sufficient to determine the payoffs for every singleton or coalition in the global pollution game. To determine the payoffs and equilibria of the coalition formation game we need information on the sharing of coalition surplus. Surplus is shared proportional to claims. Table 2 presents the input data for the claims specified in section 3. The table does not report egalitarian claims which are the same for all. Also the table does not report abatement cost claims which are coalition sensitive.

Coalition membership is most attractive for a region if it has a high claim and receives a large share of the surplus. So we expect to find EEC and USA in a coalition if surplus sharing is according to income or damages. EEX and CHN receive the largest shares under population claims, CHN and IND under ability-to-pay claims, USA and CHN under emissions claims, and BRA and DAE under inverse emission claims.

Table 2: Overview of claims

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Regions	Income [(a)(b)]	Population [(b)(c)]	Ability-to-pay [(d)]	Emissions in 2010 [(e)]	Inverse emissions in 2010 [(f)]	Damage cost shares[(g)]
	(billion US$)	(million inhabitants)	$(US\$)^{-1}$	(Gton)	$(Gton)^{-1}$	(%)
USA	8845	305	431	2.42	0.41	22.6
JPN	5584	124	386	0.56	1.80	17.3
EEC	9579	375	445	1.40	0.71	23.6
OOE	1902	142	523	0.62	1.61	3.5
EET	405	120	736	0.51	1.93	1.3
FSU	501	287	863	1.00	1.00	6.7
EEX	1650	1602	1000	1.22	0.82	3.0
CHN	1021	1340	1057	2.36	0.42	6.2
IND	458	1145	1257	0.63	1.56	5.0
DAE	972	207	679	0.41	2.47	2.5
BRA	774	190	703	0.13	7.81	1.5
ROW	1119	584	852	0.70	1.43	6.8
WORLD	32810	6421	-	11.96	-	100.0

Notes: (a) Data refer to the level of GDP in 2010 in 1985 US$. Global figure for 2010 level taken from DICE model and regional shares from table 1.1 of World Bank (2002). (b) Data for individual countries was aggregated into our 12 regions following Babiker et al. (2001). (c) Data refer to the level of population in 2010. Extrapolated figures from 2000 levels using information from table 2.1 of World Bank (2002). (d) From columns 2 and 3 for $\gamma = 0.25$. (e) Own calculations from STACO. (f) From column 5 for $\gamma = 1$. (g) STACO calibration, Finus et al. (2003).

5 Results and discussion

The STACO model is used to generate the payoffs for every possible coalition structure (2^{12}–12 = 4084 in a 12 regions model) for the sharing schemes described above. STACO performs a stability check and identifies the internally stable coalitions (where no member would want to leave) and the externally stable coalitions (where no singleton would want to join). The findings for the 8 sharing schemes and the benchmark cases (singletons coalition structure and the grand coalition) are summarised in Table 3.[5] The stable coalitions for each scheme are listed in column 2. Column 3 reports the global annual emission reduction and columns 4-6 report costs, benefits and the resulting net benefits from abatement. Note that a considerable amount of benefits is obtained under the singletons coalition structure. The additional net benefits due to coalition formation are reported in column 7 as the sum of coalition surplus and external benefits; in column 8 this is expressed as a percentage.

There are several findings. It can be seen from Table 3, column 7, that for all sharing rules considered the remaining singletons receive large shares of the benefits generated by the

[5] For a more detailed discussion of the benchmark cases see Finus *et al.* (2003).

coalition. This indicates that there are strong incentives to free-ride. Accordingly, the stable coalitions we find are small and comprise of only two regions for most sharing schemes, but larger stable coalitions of three or four regions exist for some sharing schemes. However, transfer schemes enhance stability. We find stable coalitions for all rules considered. For comparison, Finus *et al.* (2003) look at results from the STACO model without considering transfers; they do not find any stable coalition in this case.

Table 3: Overview of results

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Sharing scheme (benchmark case)	*Members of coalition*	*Global annual emissions reduction*	*Global abatement costs*	*Global benefits*	*Global net benefits*	*Coalition surplus + external benefit*	*Benefits relative to grand coalition*
		Mton	bln US$ over 100 years	bln US$ over 100 years	bln US$ over 100 years	bln US$ over 100 years	%
(Singletons)*		553	109	2,069	1,960	0+0	0.0
(Grand coalition)*	USA, JPN, EEC, OOE, EET, FSU, EEX, CHN, IND, DAE, BRA, ROW	2563	3,553	9,584	6,031	4071+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	1030	436	3,854	3,418	264+1194	35.8
Inverse emissions	EET, BRA	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, ROW	683	155	2,555	2,400	17+423	10.8

* The benchmark cases are not stable coalition structures.

The design of the transfer schemes is important. Our result is strikingly different from the findings of Altamirano-Cabrera *et al.* (2004) who consider sharing of emission permits and not, as in this paper, sharing of net benefits from coalition formation. Altamirano-Cabrera *et al.* (2004) find a total of 4 stable coalitions for grandfathering schemes of emission permits; they do not find any stability for any of the "equitable rules" they consider. To understand the difference notice that the following holds:

PROPOSITION 3: In a climate coalition (cartel) formation game with linear abatement benefits and with surplus sharing all two-player coalitions are internally stable.

Proof: In such game abatement is a global public good. Consider coalitions K' and K with $K' \subset K$ and $K' \neq \emptyset$. It holds that $q^K > q^{K'}$ as the larger coalition will abate more and the singletons maintain their dominant strategy (Proposition 2). Hence, it also holds that the coalition surplus is increasing in coalition size, $S^K > S^{K'}$. Suppose now $K' = 1$. Then, for any two-player coalition *K*, it holds that $\sum_{i \in K} \pi_i(K) > \sum_{i \in K} \pi_i^*$. Hence, there always exists a positive surplus to be shared and for all $i \in K: \pi_i(K) > \pi_i(K - \{i\}) = \pi_i^*$.

We observe that the use of egalitarian claims, population claims, ability-to-pay claims and inverse emission claims is not very successful in terms of emission reduction and in terms of net benefits as compared to the singletons case. Abatement cost claims give a mixed picture. Sharing according to regional income and damages is more successful. The best results are obtained when claims are according to emissions. The stable coalition found for that case comprises of USA, EET, EEX and CHN and achieves about 35% of the gains that the grand coalition would achieve.

Another observation is that CHN always joins the coalition except for the "extreme" case of inverse emissions. The explanation here is straightforward. Due to low marginal abatement cost CHN is an attractive partner in a coalition. But it depends on the sharing rule who will sign an agreement with CHN. For example, with an equal sharing rule USA or EEC are not involved. On equal sharing CHN would receive a too large share of the surplus and it is better for USA or EEC to take a free-rider position. A similar situation arises with sharing according to population or ability-to-pay. The situation is different with income claims and damages claims. In these cases USA or EEC can reap more of the benefits, sufficiently much to make the free-rider position unattractive.

In the "extreme case" of inverse emissions there are coalitions with BRA. The intuitive explanation is as follows. With inverse emission claims BRA has by far the largest claim. This makes it attractive for BRA to join any existing coalition which makes them externally unstable. Coalitions with BRA, however, are unattractive for other coalition partners, which makes them internally unstable, unless the coalition is of size 2 (see Proposition 3). Also note that BRA has little options for CO_2 emission abatement and, hence, high abatement costs. Coalitions with BRA achieve very little as compared to the singletons benchmark case.

More generally, the following pattern emerges. As CHN has by far the lowest abatement costs, it has an incentive to join (almost) any two-player coalition. CHN's low cost abatement options generate a high coalition surplus of which it receives a sufficient share under almost every reasonable rule. Therefore, (almost) every two-player coalition not involving CHN will be externally unstable. Hence, if a two-player coalition is stable it is likely to involve CHN. From proposition 3 we know that every two-player coalition is *internally* stable. However, it is, in general, attractive for others to join a coalition including CHN, in particular for regions with large claims. Thus, where we find stable two-player coalitions they will consist of CHN and the region with the largest claim. This pattern applies in a straightforward manner to income claims ({EEC, CHN}), population claims ({EEX, CHN}), inverse emission claims ({CHN, BRA}), and damage cost claims ({USA, CHN} and {EEC, CHN}). This simple pattern does not apply to abatement cost claims as abatement costs are coalition dependent. In this case, seven (out of eleven) two-player coalitions with CHN are stable.

In the remaining cases of equal sharing, ability-to-pay claims and emissions claims we find coalitions of size three or more. The subsequent analysis seeks to identify the factors which are relevant for the composition of stable coalitions. Can we identify regions that are more likely to join a coalition than others? In general, in our setting, regions are described by three parameters: marginal abatement cost, marginal benefits, and the claims to a coalition surplus. For the decision whether or not to join a coalition a region compares its share of the surplus when joining a coalition with its free-rider surplus. First, consider the impact of marginal abatement costs. Regions which have low marginal abatement costs contribute more to the size of the coalition surplus. Hence, with other things equal, we would expect to find the regions with the lowest marginal abatement costs in a coalition. Second, the impact of marginal benefits is ambiguous. On the one hand, high marginal benefits stimulate coalition partners to abate more which contributes to a higher coalition surplus. On the other hand high marginal benefits are an incentive to free-ride. One can define a free-rider surplus as the product of marginal benefits from abatement and the additional abatement of the coalition (compared to the singletons coalition structure).[6] We presume that high marginal benefits cause stronger incentives to free-ride than incentives to join the coalition. This is because the additional surplus of joining will have to be shared with other coalition members. Other things being equal a region is more likely to be in coalition if its marginal benefits are low. Third, with unequal claims, a region is more likely to join a coalition if its claims are high.

We use this argument to construct a rough indicator for the relative advantage from coalition membership. We use the following ingredients: (i) marginal abatement cost at 50 Mton per year (Table 1, column 3), c', (ii) marginal benefits (Table 1, column 5), b', and (iii) the share of total claims (Table 2). Rescaling the cost and benefits parameters, we propose the following coalition membership index *I*:

$$I = \frac{\ln(1+b_i')}{\ln(1+c_i')} \cdot \frac{1}{(\ln(1+b_i'))^2} \cdot \frac{\lambda_i}{\sum_{j \in N} \lambda_j} .$$

The first factor captures surplus size; the second captures free-rider incentives; the third captures 'the size of a region's share in a coalition. A region is more likely to be a coalition member if it has a high coalition membership index, that is if its marginal abatement costs are low, if its marginal benefits are low, and if its share of the surplus is high. Of course, such indicator cannot work "precisely" as marginal abatement cost and the share of the surplus a

[6] Marginal benefits are assumed to be constant and are given in Table 1 column 5; in the singletons coalition structure marginal benefits equal marginal abatement costs.

region receives will be coalition dependent. A general coalition membership index cannot be constructed as this requires to attach weights to each component of the index which will differ between claim types. However, based on parameters c_i', b_i' and λ_i we can obtain a partial ordering of coalition membership: If region *i* is a coalition member, then region *j* with $c_j' < c_i'$, $b_j' < b_i'$ and $\lambda_j > \lambda_i$ will also be a coalition member. If region *i* is not a coalition member, then region *j* with $c_j' > c_i'$, $b_j' > b_i'$ and $\lambda_j < \lambda_i$ cannot be a coalition member either.

The index we suggest is reported in Table 4. For equal sharing the highest coalition membership indices are reported for CHN, EET and IND. These regions form the only externally stable coalition of the about 100 internally stable coalitions for the case of equal sharing. This confirms our expectation. In the case of income claims EEC has a higher index than CHN. In this case the index identifies only USA correctly as a coalition member. For the cases of population claims, ability-to-pay claims, inverse emission claims and damage cost claims the index performs well, identifying correctly members of stable coalitions. For emission claims three of the four coalition members are correctly identified.

*Table 4: Coalition membership index**

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Regions	*Equal sharing*	*Income*	*Population*	*Ability-to-pay*	*Emissions*	*Inverse emissions*	*Damage cost*
USA	0.22	**0.73**	0.13	0.13	**0.54**	0.05	**0.61**
JPN	0.05	0.11	0.01	0.03	0.03	0.05	0.11
EEC	0.10	*0.35*	0.07	0.06	0.14	0.04	0.29
OOE	0.23	0.16	0.06	0.16	0.14	0.20	0.10
EET	**0.47**	0.07	0.11	**0.46**	***0.24***	**0.49**	0.07
FSU	0.28	0.05	0.15	0.32	*0.28*	0.15	0.22
EEX	0.25	0.15	**0.73**	0.33	**0.30**	0.11	0.09
CHN	**0.79**	***0.30***	**1.99**	**1.13**	**1.88**	0.18	**0.59**
IND	**0.29**	0.05	0.61	**0.48**	0.18	0.25	0.17
DAE	0.25	0.09	0.10	0.23	0.10	0.34	0.08
BRA	0.15	0.04	0.05	0.14	0.02	**0.63**	0.03
ROW	0.22	0.09	0.24	0.25	0.15	0.17	0.18

* Members of stable coalitions are indicated with bold figures. Italics indicate the two cases where coalition membership is not correctly described by the index.

The most successful coalition we find is when claims are according to emissions. As can be seen from Table 5 the success of the coalition for the global surplus depends largely on the presence of both, USA and CHN, in the coalition. Three players coalitions {EET, EEX, CHN} and {USA, EET, EEX} are less successful than {USA, CHN}, which achieves a global surplus of 996 bln US$ over 100 years (not reported in the table). In the case of emissions claims CHN has strong incentives to join as it has high claims (and obtains a large share of the surplus when joining) *and* it has low abatement costs. In fact, no coalition that does not include CHN is externally stable. USA joins CHN because under emission claims USA receives the largest share. EEC has the third largest claim, but they have a strong free-rider incentive. USA and CHN are joined by EET and EEX who receive lower shares than EEC but have less incentive to free-ride. The simple intuitive explanation why emission based claims are more successful than any alternative rule considered here is as follows. A high level of emissions is linked to better opportunities for abatement and, hence, low abatement costs. Coalitions that include regions with lower abatement costs create a larger surplus. Under emissions claims these regions are encouraged to join a coalition.

Table 5: Results for coalition structure {USA, EET, EEX, CHN} and neighbouring coalitions*

Regions	EET, EEX, CHN	USA, EEX, CHN	USA, EET, CHN	USA, EET, EEX	USA, EET, EEX, CHN
	share of coalition surplus (bold) or free-rider surplus (bln US$ over 100 years)				
USA	94	**83**	**85**	**26**	**96**
JPN	72	265	248	66	308
EEC	98	362	339	90	421
OOE	14	53	50	13	62
EET	**2**	20	**19**	**6**	**22**
FSU	28	104	97	26	120
EEX	**4**	**45**	43	**14**	**52**
CHN	**7**	**81**	**83**	24	**94**
IND	21	77	72	19	89
DAE	10	38	36	10	44
BRA	6	23	22	6	27
ROW	28	104	98	26	121
World	386	1,256	1,191	326	1,458

** This coalition is internally and externally stable.*

6 Conclusion

Greenhouse gas abatement is a global public good. It is hardly surprising that the implementation of the Kyoto protocol is hampered by adverse incentives of potential coalition partners although a large coalition could create large scale global benefits. Due to the public goods character of abatement the very success of a coalition undermines its viability. The more abatement a coalition achieves the stronger grow the incentives to free-ride. This paper explores the role of surplus sharing for coalition stability. We have identified the stable coalitions for a set of different modes of surplus sharing; in particular we examine equal sharing and sharing proportional to claims. The results show that some of the sharing schemes, for example when claims reflect historical responsibilities (inverse emissions), generate only small and ineffective coalitions ({EET, BRA} and {CHN, BRA}). These achieve only 0.5% and 2.4% of the potential surplus of globally optimal carbon abatement, respectively. In the given set of rules proportional sharing with emission claims performs best. The coalition {USA, EET, EEX, CHN} achieves about 35% of the potential surplus. Emissions claims set the right incentives to get the large emitters with low abatement costs "into the boat". As a general pattern one can observe coalitions where CHN is joined by the region with the largest claim. CHN provides low-cost abatement options and is, thus, an attractive coalition partner for regions with a large claim. Hence, CHN is joined by EEC under income claims, by EEX under population claims, by IND (and others) under ability-to-pay claims, by USA (and others) under emission claims, by BRA with inverse emission claims, and by USA under damage cost and abatement cost claims.

This paper studies the performance of a set of given sharing rules that have been proposed in the debate on climate change policies. The task for subsequent research is to use these insights for the design of sharing rules which will stabilise larger and more successful coalitions. For the success of a coalition it is important to get the regions with low abatement costs to join. But these will do little unless regions with high marginal damage costs are also joining. Only this would lead to a large scale internalisation of the externalities from carbon emissions.

Finally, our results indicate that concerns for equity, taking ability to pay or historical responsibilities into account, may well be counterproductive as surplus sharing under such rules leads to small and ineffective coalitions.

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