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Oldenburg Discussion Papers in Economics

Strategic Complements in International Environmental Agreements: a New Island of Stability

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V – 393–16

August 2016

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August 23, 2016

Abstract

International environmental agreements have had varying success in the past; the theoretical literature on international environmental agreements (IEAs) explains why freeriding is so common. This paper allows for two strategically different types of countries. Damage functions are concave for some countries (contrary to the standard convexity assumption). This leads to strategic substitutes and complements in emissions reduction within the same model. The interaction of both country types can lead to a stable agreement that is larger than in the standard case, and to more global abatement. Such a stable agreement constitutes an island of stability in addition to the small standard agreement.

*Earlier versions of this paper were presented in April 2015 at the Second Environmental Protection and Sustainability Forum in Bath, UK, and in June 2015 at the European Association of Environmental and Resource Economists 21st Annual Conference (EAERE) in Helsinki, Finland.

1 Introduction

International environmental agreements (IEAs) suffer from the well-known freerider problem: Countries which are not committed to membership of an agreement have very low incentives to reduce emissions if the members of an agreement do so. In light of the fundamental implications of climate change, this pessimistic analysis is yet of little help. What alternatives can be offered to improve prospects for reaching an agreement on global emission reductions?

The root of this pessimism lies in countries' emissions being strategic substitutes, i.e. if one country reduces emissions, the other countries respond by expanding them. Established models of global emissions games assume strategic substitutes in emissions, both in the theoretical (e.g. in the seminal work of Hoel, 1991; Carraro and Siniscalco, 1993; Barrett, 1994) and in the simulation literature (e.g. Bosetti et al., 2006; Nagashima et al., 2009; Lessmann et al., 2009). This assumption partially drives the common trade-off between broad-but-shallow and deep-but-small IEAs. However, some authors have shown that there are good theoretical or empirical reasons that emissions can also be strategic complements for some countries, e.g. due to technological spillovers, trade, or adaptation to climate change (Fredriksson and Millimet, 2002; Copeland and Taylor, 2005; Ebert and Welsch, 2009; Eisenack and Kähler, 2015). It is thus important to know whether strategic complementarity might ease the provision of a global public good in a self-enforcing IEA. Only few studies up to date analyse the implications of strategic complements in global emissions games. Ebert and Welsch (2009); Eisenack and Kähler (2015); Heugues (2012a) consider the case of two countries with quite general classes of damage functions. While the latter two endogenise the sequence of play in a Stackelberg setting, the former two consider adaptation to damages as a further decision variable. For the n country case, Heugues (2012b) determines stable agreements for specifically parametrized damage functions. In her setting, all countries' emissions are strategic complements. Our paper determines stable agreements for the n country case with heterogeneous country types and quite general damage functions: while some countries' emissions are strategic complements, others' are substitutes. We also explore how game equilibria depend on the number of countries of each type.

We analyse a three-stage game with emissions of countries as decision variables. Countries can have either convex or concave damage functions, which is tied to strategic substitutes or complements (Heugues, 2012a; Eisenack and Kähler, 2015). In the first stage, countries decide about being members of an agreement. In the second stage, the agreement jointly acts as a Stackelberg leader by maximizing their sum of payoffs. In the third stage, followers of all country types play a simultaneous Nash game for the given agreement structure and the the agreement's emissions. The paper analyses how the agreement's maximization problem depends on the number and type of the non-members.

It is shown that non-members with a convex damage function react as free-riders, while non-members with a concave damage function emit less in the equilibrium if the agreement reduces emissions sufficiently. We find that, independently of the number of countries with strategic complements, the usual small agreements remain stable. However, we also find than an additional range of stable agreement sizes exists under reasonable conditions. These agreements are larger, have lower total emissions, and are Pareto-superior to the usual stable agreements. They are yet not much larger than the usual agreements. We call such agreements 'islands of stability' since their size range can be disconnected from the usual range of stable agreement sizes, and since the range is small.

We first introduce the game structure with n countries of two types in section 2. In section 3 the model is solved by backward induction. Finally we discuss the findings with a view on parameter influence in section 4 and conclude with a summary of results and an outline of further steps to understand agreement stability. The appendix contains the proofs.

2 Model Structure

This paper determines stable international environmental agreements of multiple countries that deal with a public bad. In the absence of a supranational agency that can enforce a first-best level of mitigation, the agreement has to be self-enforcing and will typically not include all countries. In this section, the variables, basic assumptions and the game structure are introduced.

2.1 Variables and Assumptions

The model considers n countries, each denoted by subscript i. Countries choose their own emissions $e_i \in [0, 1]$, i.e. we assume that per country emissions have an upper bound due to capacity constraints. Aggregate emissions by all countries except i are denoted by e_{-i}, so that total emissions are $e = e_i + e_{-i}$.

Emissions are assumed to be a substitutable input for production, that at the same time generate increasing damages D_i, depending on the global emissions level. Therefore mitigation of emissions is a public good. We assume countries' payoff-functions of the form $\pi_i = b \cdot e_i - D_i(e)$ with $D_i(0) = 0, D_i' > 0$. Damages are non-linear to account for strategic substitutes and complements as will become clear below. While our assumptions about damages are rather general, benefits $b \cdot e_i$ are restricted to the linear case in order to keep the analysis tractable (cf. Asheim et al., 2006; Barrett, 1999, 2001). More generalization requires future work.

There are two types of countries, α and β, which differ in the properties of their damage functions. All countries of the same type are identical:

$$\alpha \text{ countries: } D_i'' > 0, D_i' < b, \tag{1}$$

$$\beta \text{ countries: } D_i'' < 0. \tag{2}$$

This means that α countries have convex damage functions whereas β countries have concave damage functions. The former are those countries that are conventionally considered in the literature on international environmental agreements and the integrated assessment of climate change. The latter type of countries, being less conventional, lead to strategic complements, as has been investigated for other settings by Ebert and Welsch (2012); Heugues (2012a); Eisenack and Kähler (2015), who also discuss possible reasons for β countries to exist. Eq. (1) further implies that there is no incentive for a single α country to reduce emissions – a common assumption to focus the analysis on the interesting case of dominant freeriding incentives.

The number of α countries that are members of an agreement is denoted by $x \geq 0$, and those α countries that are not members by $y \geq 0$. The total number of β countries is $z \geq 0$, so that $x + y + z = n$. In our notation, aggregate emission of all countries belonging to a group g are accordingly denoted by e_g, while $e_{-g} = e - e_g$ denotes the aggregate emissions of all countries not belonging to that group.

In order to focus our analysis, we further impose for all α countries i the assumption:

$$\forall x, y \quad \exists e < n : \quad (x + y) \cdot D_i'(e) = b, \tag{3}$$

i.e. if all α countries would optimize their joint payoff, it is profitable to abate at least a little. Together with Eq. (1), this ensures that cooperation can yield gains, but unilateral action from single α country is never individually rational. Without these assumptions, we would also investigate uninteresting cases.

2.2 Game Structure

We determine the subgame perfect equilibrium of a three stage game. In the first stage (A) an agreement can be formed. Each α country anticipates the outcomes of the subsequent stages and choose individually whether it joins the agreement or not. The common solution concept we employ at this stage is internal and external stability (D'Aspremont et al., 1983). We assume that β countries do not become members. While the main reason for this is tractability, our numerical experiments with allowing β countries to become members have shown that game equilibria do not substantially change. In the second stage (B) the agreement with x members chooses the emissions of its members in order to optimize its joint payoff. In the third stage (C) the non-members (y α and z β countries) choose their emissions simultaneously.

Thus, the agreement acts as a Stackelberg leader committing to its emissions first, then the non-members play a Nash subgame. We thus follow the common rationale of Barrett (1994), and not the equally common of Carraro and Siniscalco (1993), where all emission decisions are made simultaneously. With the latter rationale, strategic complementarity would not effect the game equilibrium (Eisenack and Kähler, 2015). The paper analyzes the stages in reverse order by backward induction.

3 Game Equilibria

3.1 Stage C: Emissions of Non-Members

First, determine the best response correspondence of each of the y non-member α countries. By individually maximizing their payoff $\pi_i = be_i - D_i(e_i + e_{-i})$ for given emissions of all other countries e_{-i}, Eq. (1) implies the corner solution $e_i = 1$. This is a dominant strategy. Thus, the α countries which are not members of the agreement emit $e_y = y$ in total, independent from the decisions of the members of the agreement and the non-member β countries.

Second, turn to the best response correspondence of each of the z non-member β countries. They also individually maximize their payoff $\pi_i(e_i, e_{-i}) = be_i - D_i(e_i + e_{-i})$. Note that for β countries, $\frac{d^2\pi_i}{de_i^2} = -D_i'' > 0$, so that the first-order-condition would not yield a payoff maximum. Accordingly, a non-member β country compares the corner solutions. Define $\Delta(e_{-i}) := \pi_i(1, e_{-i}) - \pi_i(0, e_{-i}) = b - D_i(1 + e_{-i}) + D_i(e_{-i})$. The sign of Δ then determines the reaction. Observe that $\Delta' = D_i'(1 + e_{-i}) + D_i'(e_{-i}) > 0$ due to Eq. (2). Thus, Δ has at most one zero, is negative to the left of $\tilde{e}$, and positive to the right of $\tilde{e}$. We assume here and in the following that there exists an $\tilde{e}$ so that

$$\Delta(\tilde{e}) = 0. \tag{4}$$

This yields the best response correspondence

$$e_i = \begin{cases} 0 & \text{if } e_{-i} < \tilde{e}, \\ 1 & \text{if } e_{-i} > \tilde{e}, \\ \{0, 1\} & \text{if } e_{-i} = \tilde{e}. \end{cases} \tag{5}$$

While the β country chooses a unique corner solution in the first two cases, it is indifferent between them in the third case. Note that this intermediate result can be characterized as a generalized notion of strategic complements (Bulow et al., 1985). While the original definition rests on a best response function with a positive derivative, we have a non-decreasing correspondence in our case.

Further note that the existence of $\tilde{e}$ is not implied by the other assumptions made so far. However, the cases where it does not exist are not very interesting for our further analysis: If Δ would be always always positive, β countries would dominantly play $e_i = 1$, so that they would not behave differently from non-member α countries. If Δ would be always negative, β countries would dominantly play $e_i = 0$, so that they can be ignored and the analysis would be reduced to the common case without β countries.

Finally, turn to the Nash equilibrium in stage (C). The objective is to determine the aggregate emissions $e_y + e_z$ when all non-member of the agreement simultaneously chose their emissions, given the emissions e_x of the agreement members, and the choices of all non-members. The situation is simple for the non-member α countries since they have dominant strategies.

The situation is more tricky for a β country i. If the total emission of the α countries $e_x + e_z$ are already larger than $\tilde{e}$, all β countries would chose $e_i = 1$. In contrast, if the total emission of the α countries $e_x + e_z$ are so small that even $e_x + e_z + e_y < \tilde{e}$, all β countries would chose $e_i = 0$. But what happens in the case where $e_x + e_z < \tilde{e}$, but the choice of the other β countries would make a difference whether $e_{-i} \lesseqgtr \tilde{e}$? What if $e_{-i} = \tilde{e}$? This is clarified by the following proposition.

Proposition 1. *Assume that Eq. (1) and Eq. (2) hold, $z \geq 1$, and that $\tilde{e}$ exists according to Eq. (4). Let e_x be the given emissions of the agreement members. Then, the only Nash equilibria of stage (C) are:*

$$\textit{if } e_x \leq \tilde{e} - y \textit{ then } \forall \beta \textit{ countries } i : e_i = 0, \textit{ and } e_z = 0, e = e_x + y, \tag{6}$$

$$\textit{if } e_x \geq \tilde{e} - y - z + 1 \textit{ then } \forall \beta \textit{ countries } i : e_i = 1, \textit{ and } e_z = z, e = e_x + y + z. \tag{7}$$

Note that the Nash equilibrium is not always unique. If $\tilde{e} - y - z + 1 \leq e_x \leq \tilde{e} - y$, which is equivalent to $\tilde{e} - z + 1 \leq e_x + y \leq \tilde{e}$, the β countries either symmetrically chose $e_i = 0$ or $e_i = 1$. If the emissions of all α countries have a medium size, both a low emissions and a high emissions outcome are possible in equilibrium. Once one of those strategy profiles is given, no β country has an incentive to deviate from that. Consequently, the proof strategy is to show that both strategy profiles are consistent with the best response correspondence of each country. Finally, the proof in appendix A shows that there are no further consistent strategy profiles.

For the remainder of the paper, we ease analysis by resolving the ambiguity of equilibria in the proposition. The proposition's result can be understood as a "response correspondence" of the aggregate of non-member α countries and β countries (that play non-cooperatively). For intermediate levels of e_x, this correspondence has a two-valued image. We chose a non-decreasing selection from this correspondence as follows. Let $\hat{e} \in [\tilde{e} - y - z + 1, \tilde{e} - y]$. We then assume that the stage (C) equilibria

$$e_z = \begin{cases} 0 & \text{if } e_x + y \leq \hat{e}, \\ 1 & \text{if } e_x + y > \hat{e}, \end{cases} \tag{8}$$

realize. It is further reasonable to consider only those cases in the paper where

$$0 < \hat{e} < x + y. \tag{9}$$

If $\hat{e}$ lies outside of these bounds, the results would be trivial because the non-convexity property of the β countries would not have any impact on the game.

3.2 Benchmark Solution

The results so far allow to determine the non-cooperative Nash solution, as it corresponds to $x = e_x = 0$. This will help to discuss the results of the three stage game equilibrium. There is a unique Nash equilibrium. The α countries emit $e_i = 1$ each, together $e_y = y$, as always due to dominant strategies. Due to Eq. (9), $e_x + y = y > \hat{e}$. Thus, the β countries emit $e_z = 1$ each, too. Therefore, global emissions are $e = n$. There is no abatement in the non-cooperative Nash solution.

3.3 Stage B: Emissions of Agreement Members

The agreement of α countries maximizes the aggregated payoff of all members. To do so, they coordinate and choose emissions of each member. We simplify this and let the agreement directly choose their aggregated emissions e_x[1]. Together with Eq. (8), the agreement's optimization problem thus reads

$$\max_{e_x} \quad \Pi_x = e_x \cdot b - x \cdot D_i(e_x + y + e_z) \tag{10}$$

$$s.t. \quad e_x \in [0, x], \tag{11}$$

$$e_z = \begin{cases} 0 & \text{if} \quad e_x + y \leq \hat{e} \\ z & \text{if} \quad e_x + y > \hat{e} \end{cases} \tag{12}$$

Recall that the damage function D_i is identical for all members of the agreement, and that it has the properties Eq. (1) and Eq. (3).

The first-order condition for an interior solution would evaluate to

$$\frac{b}{x} = D_i'(e_x + y + e_z). \tag{13}$$

In our particular situation however, the function $D_i(e_x + e_y + e_z)$ has a discontinuity at $e_x = \hat{e} - y$ because there e_z changes from 0 to z. This results in a more complicated solution of the agreement's optimization problem. The agreement chooses the emissions of its members according to proposition 2, proof is in appendix B.

Proposition 2. *Assume that $x > 0$, $y, z \geq 0$ and $\hat{e} < x + y$. Let i be an α country. Define $f(e, x) = be - xD_i(e)$. Let F be the solution of*

$$b \equiv xD_i'(F(x)). \tag{14}$$

[1] Due to linear benefits of emissions it is not relevant here how emissions are distributed among agreement members, as long as the benefits are distributed evenly.

case no.	condition $\hat{e}$	condition $F(x)$	outcome e_x^*	e_z^*	e^*
1	$\hat{e} < y$	$x + y + z < F$	x	z	$x + y + z$
2		$y + z < F \leq x + y + z$	$F - y - z$	z	F
3		$F \leq y + z$	0	z	$y + z$
4	$y \leq \hat{e} < x + y$	$x + y + z < F$	x	z	$x + y + z$
5		$\hat{e} < F \leq x + y + z$			
		and $bz < f(F, x) - f(\hat{e}, x)$	$F - y - z$	z	F
6		$\hat{e} < F \leq x + y + z$			
		and $bz > f(F, x) - f(\hat{e}, x)$	$\hat{e} - y$	0	$\hat{e}$
7		$y < F \leq \hat{e}$	$F - y$	0	F
8		$F \leq y$	0	0	y

Table 1: Stage B game equilibria.

Then, F is strictly decreasing in x

$$F'(x) < 0. \tag{15}$$

The unique stage B equilibrium is given by Tab. 1. If $bz = f(F, x) - f(\hat{e}, x)$, then both the cases 5 and 6 in Tab. 1 are game equilibria in stage B.

In cases 1 through 3 of Tab. 1, the agreement can not reduce emissions sufficiently so that the β countries abate as well. Of the other cases, 4 and 8 are corner solutions of no and full abatement, respectively. Case 3 is a 'normal' internal solution (as common in the IEA literature without strategic complements). In case 6, the agreement reduces emissions so that global emissions fall below $F(x)$ (which would be optimal in the absence of strategic complements). The reduction is just enough to induce a choice of $e_i = 0$ by the β countries. In case 7 the 'normal' internal solution (similar to case 3) for the agreement is low enough that the β countries choose $e_i = 0$.

For the remainder of the paper, we focus our considerations on the cases No. 4 through 7 of (Tab. 1). The other cases are either very similar (case 1 is similar to case 3 and case 2 to case 5) or corner solutions that are not particular to our analysis of non-convexities (cases 3 and 8).

3.4 Stage A: Agreement Size

In this section we analyse the endogenous choice of agreement size x.

Every agreement size x yields certain global emissions $e^*(x)$ as equilibrium of stages B and C. Knowing these emissions, every α country can compare its payoff within the agreement for the actual agreement size $\frac{b}{x} - D_i(e^*(x))$ with the payoff it would get if it left the agreement $b - D_i(e^*(x-1))$. The difference between these is the value of the outside option $\Omega(x)$.

$$\Omega(x) = b - D_i(e^*(x-1)) - \frac{b}{x} + D_i(e^*(x)) \tag{16}$$

We assume that every country has a positive value of the outside option $\Omega(x)$ as long as global emissions are $e = F(x)$. A positive outside option means that a member of the agreement increases its payoff if it leaves (i.e. becomes a non-member).

$$\begin{aligned} &\text{If} && e < n, \\ &\text{then} && \Omega(x) = b - D_i(F(x-1)) - \frac{b}{x} + D_i(F(x)) > 0. \end{aligned} \tag{17}$$

This assumption is a stronger version of Eq. (1) and gives the game the form of a prisoner's dilemma; it makes cooperation (i.e. $e_i = 0$) a dominated strategy for all α countries as long as any others cooperate and emissions are $e = F(x)$ (i.e. like in the absence of strategic complements).

There is always at least one stable agreement in the stage (C) equilibrium. For $z = 0$ it is unique, for $z > 0$ there can be a second stable agreement. The size of stable agreements is given by propositions 3 and 4, proof is in appendices C and D.

Proposition 3. *Suppose that assumptions Eq. (1), (3), (17) hold and $x + y > 0$. Then there exists a stable agreement with size $x > 1$. The smallest abating agreement $\bar{x}$ that chooses emissions $e_x < x$ in stage B is internally stable. If $z = 0$ then this smallest abating agreement $\bar{x}$ is also externally stable and its size is unique. In this case, global emissions are $e = F(x)$.*

This proposition describes a small agreement, which is a standard result in the case without strategic complements (as Diamantoudi and Sartzetakis (2006) have shown for a wide variation of variables). The smallest abating agreement $\bar{x}$ forms, but no more than the minimum number of countries required for this enters the agreement. The agreement's choice of emissions is an internal solution, and global emissions are lower than in the business as usual case without a agreement. The agreement size is unique if there are no β countries.

We now come the paper's main result: If β countries take part in the game, then there can be a second stable agreement size (see proposition 4). If this larger stable agreement is one country larger than the smallest abating agreement then the larger one is stable and the smaller one is not.

Proposition 4. *Assume that Eq. (1), (2), (3), (17) hold, $x + y > 0$, $0 < \hat{e} < x + y$ and $z > 0$. If $D_i(F(\underline{x} - 1)) - D_i(\hat{e}) > b \cdot \left(1 - \frac{\hat{e} - y}{\underline{x}}\right)$ holds for any agreement size $\underline{x}$, then an agreement of this size $\underline{x}$ is stable. No other agreements except those of size $\underline{x}$ and size $\bar{x}$ (see proposition 3) are stable. An agreement of size $\underline{x}$ leads to global emissions of $e = \hat{e} < F(x)$.*

As both the (larger) agreement size $\underline{x}$ and the (smaller) stable agreement size $\bar{x}$ are stable, the latter is what we call an additional 'island of stability'. (Exception: if $\underline{x} = \bar{x} + 1$ holds, i.e. if the agreement size $\underline{x}$ from proposition (4) is exactly one country larger than the agreement size $\bar{x}$ from proposition (3), then $\underline{x}$ is stable and $\bar{x}$ is not.) Without further assumptions it is impossible to tell which of the two possible agreement sizes will be realized. This larger agreement $\underline{x}$ given in proposition 4 is the smallest one that supports global emissions of $e = \hat{e} < F(\underline{x})$. Global emissions in this case are lower than for the other agreement that is shown in proposition (3).

Welfare is also improved for every country compared to the standard case $\bar{x}$, so the larger agreement size $\underline{x}$ is a Pareto-improvement. This is obvious for non-member α countries because they simply gain from lower damages and enjoy the same benefits. β non-members also gain from lower emissions: they lower their emissions (from $e_i = 1$ to $e_i = 0$) because it gives them an additional benefit over the already beneficial situation of the mitigation effort from the agreement (which lowers their damage in absolute terms even though it increases their marginal damage). The agreement members have gains from cooperation. In particular, global emissions are so low in this situation (due to mitigation by the β countries in addition to the agreement's mitigation) that their payoff is large enough to give them a negative outside option (which is why the agreement is stable).

Whether or not $\underline{x}$ is indeed internally stable, depends on $D_i(\hat{e})$ for α countries. If the damage is small enough (i.e. if the β countries reduce their emissions sufficiently between sections 5 and 6 of Tab. 1 to drive down global emissions significantly), then $\Omega(\underline{x})$ is negative and agreements of size $\underline{x}$ are internally stable.

4 Discussion

We have shown that the existence of countries with non-convex damage functions (β countries) can allow for an island of stability with non-conventional, larger agreement size $\underline{x} > \bar{x}$ than in the case without strategic complements. In such a game equilibrium, the agreement is just large enough to induce the β countries to chose emissions $e_i = 0$, even though they are not agreement members. In the equilibrium, global emissions are lower and the payoff is larger for every country.

What happens if the number of α countries and β countries changes in the comparative statics sense? A larger number of β countries z means that emissions drop more sharply if the agreement forms at the island of stability (i.e. is large enough to achieve total emissions $e = \hat{e}$: case 6, Tab. 1). However if $\hat{e}$ remains constant, a larger z does not mean that global emissions fall to a lower level, but that they start falling from a higher level. This in turn means that less mitigation effort on behalf of the agreement is necessary to achieve the same (positive) result, and a smaller agreement may be able to do so.

This does not mean that the outside option for members of this agreement is necessarily smaller, even though it seems probable. It is possible that the border between cases 5 and 6 of Tab. 1 is reached for a smaller agreement size x, so the mitigation effort is distributed among fewer countries. If the agreement can increase emissions a little bit and still reach $\hat{e}$ the outside option for agreement size $\underline{x}$ could even grow (because $\underline{x}$ could sink). This means that even if the emissions reductions by β countries between cases 5 and 6 from Tab. 1 increase, agreement size $\underline{x}$ (which relies on case 6) may loose its stability.

Furthermore, consider that it were possible for non-member α countries to become β countries. This could stabilize the agreement because non-members would reduce more emissions, since y decreases, and $\hat{e}$ is not likely to increase. However, results depend on the dynamics between the β countries which result in the relationship between $\tilde{e}$ and $\hat{e}$. For an optimistic approach ($\tilde{e} = \hat{e}$) an α country which becomes a β country would indeed not change $\hat{e}$, thus increasing desirability of the $\underline{x}$ case. For a pessimistic approach ($\tilde{e} + z - 1 = \hat{e}$), $\hat{e}$ is reduced by 1 for every country that changes its type from α to β. This increases both costs and benefits for agreements of size $\underline{x}$; the effect on stability is ambiguous.

5 Conclusions

The paper investigates the equilibrium of an international emissions game for the case of two strategically distinct types of countries, some of which join a binding environmental agreement. While one country type has a conventional convex damage function (α countries), the other countries have concave damages (β countries). We assume that members of an agreement jointly act as Stackelberg leader, while the non-signatories of both types play a Nash game in the final stage of the game.

Due to their non-convex damage functions, β countries outside the agreement do not act as freeriders on mitigation efforts of the agreement. Instead they reduce their emissions if there is sufficient mitigation effort by the other countries. This is not a strategic choice (which could be non-credible), but individually rational. By anticipating this reaction, the agreement as Stackelberg leader has a novel incentive structure. If the emissions of its members are sufficiently low, then they can profit from the additional of cooperation by the β non-members.

We find that this leads to the possibility of a larger stable agreement which sufficiently reduces emissions to induce emissions reductions by the β countries. Then, global emissions are significantly lower than in the case without β countries, and it is also Pareto-superior. However, the smallest abating agreement size remains stable even if the larger one becomes stable, so it remains an open question which of the two potentially stable agreements would be realized.

Our model admittedly relies on the quite restrictive assumption of constant marginal gains from emissions. While this is not a very uncommon assumption (cf. Asheim et al., 2006; Barrett, 1999, 2001), it is still a strong one. However the main argument of our analysis does not rest critically upon this linearity. Instead we have chosen it because it helps keeping the model tractable. The main point of the analysis lies in the strategic complementarity of emissions abatement for some countries. Countries in and agreement can use their Stackelberg leadership position to exploit this strategic complementarity to the benefit of all countries. Therefore the results should carry over to models with diminishing marginal gains from emissions.

Further research could look into effects of β countries inside the agreement as well as multiple agreements. Based on current results and numerical experiments, we can begin to speculate about the potential outcome of such an analysis. Stable agreements contain only a small number of β countries, if any β country at all (supposed there are no transfer payments within the agreement). Eisenack and Kähler (2012) show that β countries voluntarily select the follower position to improve their payoff in the two countries case. To take this a little bit further, in a setting where countries with concave damage functions exist, a grand coalition is not required in order to come closer to the social optimum.

We thus think it is worth further exploring the effects of heterogeneous countries in international environmental agreements, in particular if countries exhibit qualitatively different strategic properties.

A Proof of Proposition 1

Proof. First, suppose that $e_x \leq \tilde{e} - y$ and $e_i = 0$ for all β countries. Consider a specific β country i. Then,

$$e_{-i} = e - e_i = e_x + y \leq \tilde{e}. \tag{18}$$

Thus, $e_i = 0$ is a best response according to Eq. (5): country i cannot benefit from unilaterally changing its strategy.

Second, suppose that $e_x \geq \tilde{e} - y - z + 1$ and $e_i = 1$ for all β countries. Consider a specific β country i. Then,

$$e_{-i} = e - e_i = e_x + y + z - 1 \geq \tilde{e}, \tag{19}$$

so that $e_i = 1$ is a best response according to Eq. (5).

Third, exclude further equilibria. (i) Consider $e_x < \tilde{e} - y - z + 1 < \tilde{e} - y$. If there would be at least one β country i with $e_i > 0$, then, $e_{-i} = e - e_i < e_x + y \leq \tilde{e}$, so that $e_i = 0$ would be the best response, a contradiction. (ii) Consider $e_x > \tilde{e} - y > \tilde{e} - y - z + 1$. If there would be at least one β country i with $e_i < 1$, then, $e_{-i} = e - e_i > e_x + y + z - 1 \geq \tilde{e}$, so that $e_i = 1$ would be the best response, a contradiction. (iii) Consider $\tilde{e} - y > e_x > \tilde{e} - y - z + 1$, and assume that there is at least one β country i with $e_i = 0$, and at least one β country j with $e_j = 1$. The choice of i would only be a best response if $\tilde{e} \geq e_{-i} = e_x + y + e_z$. The choice of j would only be a best response if $\tilde{e} \leq e_{-i} = e_x + y + e_z - 1$. Both conditions cannot hold at the same time. □

B Proof of Prop 2

Proof. [1] First, collect properties of F. If D_i fulfills the Inada-conditions, F always exists, and is positive. By taking the total differential, $F'(x) = -\frac{b}{x^2} D''_{\alpha}(F(x)) < 0$, so that

F is strictly decreasing.

[2] Now observe that the conditions in Tab. 1 cover all possibilities in terms of x, y, z. Obviously, the cases are disjoint. They are also complete (the only missing case in the table, $bz = f(F, x) - f(\hat{e}, x)$, corresponds to non-unique equilibria).

[3] Now proceed to the main part of the proof. We go through all cases, and show that the game equilibria are as given in Tab. 1. Generally, note that

$$d_{e_x}\Pi_x = b - xD'_\alpha(e_x + y + e_z)$$

$$\text{with } e_z = \begin{cases} 0 & \text{if } e_x \leq \hat{e} - y, \\ z & \text{if } e_x > \hat{e} - y, \end{cases} \tag{20}$$

$$d_{e_x e_x}\Pi_x = -xD''_\alpha(e_x + y + e_z) < 0. \tag{21}$$

[3.1] Here, $\hat{e} < y$ and $e_x \geq 0$ imply $e^*_z = z$. Thus, due to $F > x + y + z$ and the monotonicity of D'_α,

$$\forall e_x \in [0, x] : d_{e_x}\Pi_x = b - xD'_\alpha(e_x + y + z) > b - xD'_\alpha(F) = 0.$$

Thus, it is optimal so chose the corner solution $e^*_x = x$ in stage B.

[3.2] Again, the β-countries' reaction is $e^*_z = z$, so that $d_{e_x}\Pi_x = b - xD'_\alpha(e_x + y + z)$. Since $y + z < F \leq x + y + z$, the monotonicity of D'_α implies

$$D'_\alpha(y + z) < D'_\alpha(F) = b/x \leq D'_\alpha(x + y + z).$$

There exists thus, due to continuity of D'_α, a unique $e_x \in (0, x]$ so that $d_{e_x}\Pi_x = 0$. It follows from the definition of F that this solution is characterized by $F = e_x + y + z$. Sufficiency is then guaranteed by the concavity of Π_x, so that $e^*_x = F - y - z$.

[3.3] Again, the β-countries' reaction is $E^*_z = z$. The monotonicity of D'_α implies

$$\forall e_x \in (0, x] : d_{e_x}\Pi_x = b - xD'_\alpha(e_x + y + z) < b - xD'_\alpha(y + z) \leq 0.$$

The last inequality follows from $F \leq y+z$ and the monotonicity of D'_α. Thus, it is optimal so chose the corner solution $e_x^* = 0$ in stage B. Then, total emissions amount to $e^* = y+z$ in the stage B equilibrium.

[3.4] Generally,

$$\forall e_x \in [0, x] : d_{e_x}\Pi_x = b - xD'_\alpha(e_x + y + e_z) \geq b - xD'_\alpha(x + y + z).$$

The last expressions is strictly positive in case 4, so that it is optimal to choose the corner solution $e_x^* = x$ in stage B. Since $x + y > \hat{e}$, we obtain $e_z^* = z$.

[3.5 / 3.6] Now consider case 5 and case 6. Observe that

$$\forall e_x \in [0, \hat{e} - y] : d_{e_x}\Pi_x = b - xD'_\alpha(\hat{e}) > b - xD'_\alpha(F) = 0.$$

Thus, the corner solution $e_x = \hat{e} - y$ is the local maximum on the interval $[0, \hat{e} - y]$. It is yet also possible to select $e_x \in (\hat{e} - y, x]$, where $d_{e_x}\Pi_x = b - xD'_\alpha(e_x + y + z)$, so that Π_x is locally maximized at $e_x + y + z = F$ (recall the concavity of Π_x). It yet needs to be determined whether the corner solution or the interior solution is the global maximum. It holds that

$$\Pi_x(\hat{e} - y) = b(\hat{e} - y) - xD_i(\hat{e}) \tag{22}$$

$$> b(F - y - z) - xD_i(F) = \Pi_x(F - y - z) \tag{23}$$

$$\Leftrightarrow bz > f(F, x) - f(\hat{e}, x). \tag{24}$$

Thus, the last inequality implies $e_x = \hat{e} - y$, which is case 6. Otherwise, case 5 applies. If the left-hand-side and the right-hand side are equal, the payoff in the corner and the internal solution is equal, so that both decisions are game equilibria.

[3.7] Due to $y < F \leq \hat{e}$ and the definition of F, it holds that $xD'_\alpha(y) < b \leq D'_\alpha(\hat{e})$. Thus, monotonicity and continuity of D'_α guarantees $\exists^1 e_x \in (0, \hat{e} - y] : xD'_\alpha(y + e_x) = b$. This just states, by the definition of F, that $e_x = F - y$ and $e_z = 0$ together fulfill the first-order condition. This also fulfils the second-order condition since Π_x is concave. This choice is consistent with Eq. 20 and $e_x \in [0, x]$ since $0 < e_x = F - y \leq \hat{e} - y$ in case 7. Thus, the stage B equilibrium is $e_x^* = F - y$ with $e^* = F$.

[3.8] It generally holds that

$$\forall e_x \in (0, x] : d_{e_x}\Pi_x = b - xD'_\alpha(e_x + y + e_z) < b - xD'_\alpha(y).$$

The last expression cannot be positive since $F \leq y$. Thus, it is optimal so chose the corner solution $e_x^* = 0$ in stage B. Thus $e_x \leq \hat{e} - y$ since $y \leq \hat{e}$ in case 8, so that $e_z^* = 0$. Then, total emissions amount to $e^* = y$.

□

C Proof of Proposition 3

Proof. We first show that the smallest abating agreement $\bar{x}$ is stable and that for a scenario without β countries ($z = 0$) it is unique. Then we prove stability for $z > 0$.

Stability for $z = 0$: All agreements smaller than $\bar{x}$ do not abate (i.e. case 1 or 4 in Tab. 1) because $\bar{x}$ is the smallest abating agreement. A non-abating agreement is always exists $\boxed{?}$ because at least for an agreement size of $x = 1$ there is no incentive to abate (this follows directly from Eq. (1) because a single α country plays dominantly $e_i = 1$). Agreements that do not abate give no advantage for members, so there is no incentive to join. Therefore no agreement smaller than $\bar{x}$ is internally stable.

If x is larger, F is smaller due to Eq. (15). Because of Eq. (3), positive abatement (i.e. $F(x) < x$) is chosen at some agreement size. Since we know that abatement is chosen because it is profitable (F is optimal by definition), the smallest abating agreement is stable. Formally, this is the point where the outside option is negative, i.e.

$$\text{for} \quad F(\bar{x}) < n: \quad \Omega(\bar{x}) = b - D_i(n) - \frac{b}{\bar{x}} + D_i(F(\bar{x})) < 0, \tag{25}$$

because in the case of $(x = \bar{x} - 1)$ there is no abatement at all.

We know that for $z = 0$ all abating agreements larger than $\bar{x}$ are not internally stable because α countries always have a positive outside option according to (17).

To summarize for $z = 0$: Agreements smaller than $\bar{x}$ are not stable, agreements larger than $\bar{x}$ are not internally stable and a agreement of size $\bar{x}$ is beneficial for its members. In other words $\bar{x}$ is the only agreement size that gives a negative outside option. Therefore it is stable and unique.

Stability for $z > 0$: The only (possible) difference to the case of $z = 0$ is that the smallest abating agreement $\bar{x}$ could fall into case 6 of Tab. 1, so $e \neq F(x)$. If this is true, then the outside option would change to

$$\Omega(\bar{x}) = b - D_i(n) - \frac{b}{\bar{x}} + D_i(\hat{e}). \tag{26}$$

This is still negative for the same reason that applies if emissions $F(x) - y - z$ are chosen by the agreement: Any positive abatement chosen by the agreement maximizes the payoff of the members, therefore it is preferable to $e = n$. The agreement is benefitial; in other words the outside option is negative and internal stability is given, just as in the case of $z = 0$.

□

D Proof of Proposition 4

Proof. We show here that for $z > 0$ exactly one other agreement can be stable. This is true because for the smallest agreement size in case 6 of Tab. 1 the outside option is larger than in the case of $z = 0$.

The outside option Ω for the smallest agreement size $\underline{x}$ that supports case 6 from Tab. 1 is

$$\Omega(\underline{x}) = b \cdot \left(1 - \frac{\hat{e} - y}{\underline{x}}\right) - D_i(F(\underline{x} - 1)) + D_i(\hat{e}). \tag{27}$$

Now we compare this with the outside option in the standard case (i.e. within section 5). If the outside option at agreement size $\underline{x}$ is smaller for emissions $e = \hat{e}$ than for $F(\underline{x})$ (i.e. is smaller for a voluntary choice by the agreement of section 6 over section 5 in Tab. 1), then the following must hold:

$$\begin{aligned}
& b \cdot \left(1 - \frac{\hat{e} - y}{\underline{x}}\right) - D_i(F(\underline{x} - 1)) + D_i(\hat{e}) \\
& \qquad < \\
& \qquad b \cdot \left(1 - \frac{F(\underline{x}) - y - z}{\underline{x}}\right) - D_i(F(\underline{x} - 1)) + D_i(F(\underline{x})) && (28) \\
\Leftrightarrow \quad & -\frac{\hat{e} - y}{\underline{x}} \cdot b + D_i(\hat{e}) < -\frac{F(\underline{x}) - y - z}{\underline{x}} \cdot b + D_i(F(\underline{x})) && (29) \\
\Leftrightarrow \quad & \frac{b}{\underline{x}} \cdot (F(\underline{x}) - z - \hat{e}) < D_i(F(\underline{x})) - D_i(\hat{e}) && (30)
\end{aligned}$$

This corresponds exactly to the definition of section 6 (in comparison to section 5). Therefore it holds if $\underline{x}$ lies in section 6 and $(\underline{x} - 1)$ in section 5. It follows that the outside option for agreement size $\underline{x}$ is smaller than for $e = F(x)$.

Whether or not $\underline{x}$ is indeed internally stable depends on $D_i(\hat{e})$. If it is small enough (i.e. if the β countries reduce their emissions sufficiently between sections 5 and 6 of Tab. 1 to drive down global emissions significantly), then $\Omega(\underline{x})$ is negative and agreement size $\underline{x}$ is internally stable. Formally, when $\Omega(\underline{x})$ is negative, the agreement is internally stable:

$$\Omega(\underline{x}) = b \cdot \left(1 - \frac{\hat{e} - y}{\underline{x}}\right) - D_i(F(\underline{x} - 1)) + D_i(\hat{e}) < 0 \tag{31}$$

$$\Leftrightarrow \quad D_i(F(\underline{x} - 1)) - D_i(\hat{e}) > b \cdot \left(1 - \frac{\hat{e} - y}{\underline{x}}\right) \tag{32}$$

External stability is not an issue for agreement size $\underline{x}$ because other agreements (except for $\bar{x}$ as described in proposition 3) are not stable. The proof works just like the corresponding one for proposition 3:

If an α country enters the agreement within section 6 global emissions $e = \hat{e}$ do not change. In effect, damage does not change by entry here but the entering country will have to bear part of the abatement costs. Therefore entry is never attractive within section 6 of Tab. 1.

The smallest agreement of section 7 is not internally stable, as well. Compared to the outside option for $e = F(x)$, a country has a damage if it leaves the agreement $D_i(\hat{e})$ that is at least as high as $D_i(F(x-1))$ while the rest of the terms are equal.

Within sections 5 and 7 of Tab. 1 no agreement except $\bar{x}$ is stable due to (17).

Therefore no other agreement than $\bar{x}$ and $\underline{x}$ can be stable. $\square$

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